

The Conservation of Doped-Fabric Aircraft at the Science Museum, London

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Abstract

The aim of this research is to improve the approaches used in the conservation of tears in doped-fabric skins of historic aircraft. Conservation at the Science Museum in London has been based upon traditional methods of repair, adhering a fabric patch with several coats of a chemical compound called 'dope' over torn areas. This dope is not only an adhesive, but also causes the patch to shrink and thus re-stretch the doped-fabric around the tear, but alternative conservation methods are now desired as it is believed shrinkage of the patches may initiate new failures.

Research into the history of doped-fabric as a material and the doped-fabric aircraft at the Science Museum was undertaken so that the collection could be evaluated in relation to the historic record. The application of FTIR-ATR, XRD and XRF to materials retained in the Science Museum archives and of samples taken from the aircraft on display demonstrated that the aircraft were re-skinned with traditional materials expected of a historic doped-fabric aircraft rather than newer synthetic ones.

The contraction caused by applying a dope to a fabric panel, and that of a doped-fabric patch to a torn area, was measured using Resistance Strain Gauges, and it was found that the contraction of the patch influenced the strain of material around it, and that the behaviour was anisotropic between the two main fabric directions, warp and weft. Tensile loading experiments also demonstrated that historic material failed at significantly lower loads than the modern materials used for patching. Based on these findings it is recommended that alternatives to doped-fabric patching, as has been practiced at the Science Museum, should be considered due to the potential impact of the patches on surrounding historic material.

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Declaration of Originality

I confirm that this is my own work and any other works used to produce this thesis have been referenced.

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1. Introduction

1.1. Doped-Fabric Aircraft

The development of the airplane began in earnest during the early years of the 20th Century, and the first powered flight in a machine heavier than air is attributed to the Wright Brothers in 1903. The earliest aircraft were often built from wooden frames, certain areas of which would be covered to create the flight surfaces over which air could flow, generating the lift required for flight. One option for creating these flight surfaces was fabric which, although initially successful for short hops, was found to have numerous drawbacks that ultimately limited what early aircraft could achieve in terms of altitude, speed and durability.

Of great concern was the extent to which fabrics deformed under the pressure of the air flowing over the flight surface, reducing the lift generated. Fabrics, moreover, are not necessarily smooth due to inconsistencies in the weave and loose fibres that disrupt the surface of the textile, increasing the amount of drag and air resistance. Finally, the strength and durability of fabric limited aircraft performance both for health and safety, and economic concerns. Fabric was liable to damage and weakening from several causes including biological growth during periods of high Relative Humidity (RH) and mechanical damage from gradual wear and tear or sudden impact.

An improvement was therefore sought over simply covering aircraft frames with plain fabric. As well as the possibility of using alternative skins in place of fabrics, such as plywood or metal, experiments were made with chemically treating the fabric skins to improve their mechanical properties. With the development of semi-synthetic and synthetic polymers during the late 19th and early 20th Centuries new coating options, called 'dopes', began to be developed. It was found that by impregnating fabrics with dope their properties could be significantly altered, becoming taut like a drum and resulting in improved flight characteristics. Benefits of doping included creating a smoother surface and a stiffer material less likely to deform during flight, as well as increasing the life-span of the fabric.

This gave rise to 'doped-fabric' aircraft during the late 1900's and early 1910's which were an important form of powered flying machine for much of the first half of the 20th Century. Even after World War II when all metal wings and fuselages increasingly became the norm, many planes continued to use doped-fabric for control surfaces, such as ailerons and rudders, due to the lightness and responsiveness to the pilot's touch. Dopes and aircraft fabrics based on traditional practices are still commercially available, though the range of choice has

grown to include more modern materials and options not available in the early 20th Century, such as synthetic fabrics and heat shrink materials.

1.2. The Conservation Challenge at the Science Museum in London

The Science Museum possesses a collection of doped-fabric aircraft that form an important record of many key milestones, events and technical developments in aviation history, and many of the doped-fabric aircraft within the museum are unique, originating from historic firsts in world history. Examples include the Vickers Vimy, which made the first trans-Atlantic crossing in 1919, and the Supermarine S6B which marked an important technological step forwards in aviation design, setting a new air-speed record in 1931.

Given the historical importance of many of these doped-fabric aircraft, their conservation and preservation are considered important by the Conservation and Collections Care Team at the museum, but this has proved a challenging problem. The most concerning and visible signs of deterioration identified by museum staff are tears in the doped-fabric skin, which range in size from a few centimetres up to the entire length of the flight surface.

Conservators at the museum judge that these tears require treatment to reduce the visible signs of damage and prevent them from enlarging. The current conservation method involves laying a piece of new fabric over the area of the tear, and then applying several coats of modern, commercially bought dope to the area. Such practice is based on traditional maintenance techniques intended to keep the doped-fabric aircraft flightworthy by preventing the tear ends from opening further, smoothing the surface of the patch, and shrinking it to restore tautness to the wing that may have deformed when the tear opened.

Concerns have been expressed regarding this conservation approach, however, since the very properties of the patch which are so important in restoring airworthiness are suspected of falling foul of certain conservation principles and ethics which guide conservation decision making within a static museum context. Two of the most important of these ethics are that treatments should not cause further damage or deterioration to the object, and that it should be removable with minimum impact on the historic material to enable alternative future treatments if desired.

The doped-fabric patch method is thought to fail on both these counts as the contraction of the doped-fabric patch potentially introduces new forces into the surrounding historic material, thereby increasing the risk of new tears occurring elsewhere. Little is known, however, about the effect of doped-fabric patches on the substrate to which it is applied as the size of the contraction and time scale over which it occurs has not been investigated. It is also suspected that the application of new dope softens the historic dope of the underlying

substrate resulting in the two layers, that of the historic and modern dopes, intermingling. Again, no investigation of this has been undertaken to date.

A lack of knowledge regarding the individual histories of the doped-fabric skins of the aircraft within the Science Museum collection also hinders decision making, as little is known by the conservators regarding their origin or construction. It is assumed that the doped-fabric aircraft are made of traditional materials appropriate to such aircraft, but the materials used and their origin are in most cases not known with certainty. This hinders the Science Museum conservators when deciding on conservation treatment as they cannot properly evaluate what the doped-fabric is, and consequently why it matters and how it should be maintained.

There is also a lack of knowledge about the properties of doped-fabric skins in general. A wide range of factors, such as how doped-fabrics respond to changes in Relative Humidity (RH), their tensile strength, chemical composition, deterioration mechanisms, and the amount of variation between aircraft, which could potentially inform how the objects are treated and managed as museum objects, is not available. Few studies of doped-fabric aircraft have been undertaken from a museum conservation perspective, and as such many of the issues of concern and interest to conservators have never been addressed or investigated.

1.3. Research Aims and Thesis Structure

This doctoral research project is a collaboration between the Science Museum and Imperial College London to address the lack of research into the material properties and conservation of doped-fabric aircraft. The main research question is to evaluate the suitability of using doped-fabric in the context of the Science Museum for the long-term preservation of its doped-fabric aircraft. As has already been highlighted, conservators suspect that the treatment may cause further damage, but have no object way of establishing this. To answer this question methodologies to measure the effect of doped-fabric patching, which could be applied in both a controlled laboratory setting, and in real-world settings directly on the aircraft were developed. The historical context of the Science Museum collection was also explored to enable more informed decisions about their care and preservation to be made.

The thesis comprises three sections. Section A, Chapters 2-5, explores the historical, museum and conservation context in which the aircraft are being preserved. Chapter 2 reviews the historical literature and archival sources pertaining to the development of doped-fabric to identify how and what doped-fabric aircraft are made of, and Chapter 3 provides a review of the aircraft housed at the Science Museum to better understand how they have evolved over the years and the museum context in which they are currently cared for. Chapter 4 discusses the

conservation profession's culture, ethos and principles to illustrate how and why certain conservation approaches may or may not be acceptable and considers the conservation literature on doped-fabric aircraft within this context. Chapter 5 concludes the section with a literature review into the material properties and conservation research into materials related to doped-fabric aircraft, including textiles, plastics and paintings.

The second section, Chapters 6-10, presents the results of the analytical work undertaken to characterise and understand the properties of doped-fabric. Chapter 6 describes the sampling of historic materials used in this research and the experimental methodology to prepare substitute, surrogate samples of doped-fabric. The results of chemical analysis used for identifying the materials from which the doped-fabric aircraft at the Science Museum are constructed are presented in Chapter 7. The effect of dope application, its response to fluctuations in Relative Humidity and the implications of patching are covered in Chapters 8, 9 and 10, respectively and were primarily investigated using Resistance Strain Gauges (RSG) to measure the strain behaviour of modern surrogate materials and the doped-fabric skins of aircraft on display. The application of RSG's are not widespread in conservation studies, but were used in this context to enable *in-situ* monitoring of doped-fabric skins in a real-world setting.

The final section, Chapters 11-13, provides a discussion of the conservation implications of the experimental work, placing the results into the context of conservation principles and ethics, followed by conclusions and suggestions for further work.

2. The Development and Production of Doped-Fabric Aircraft

Before undertaking a review of the Science Museum's collection and the conservation challenge it is necessary to have a more general understanding regarding the construction, design and materials used in making doped-fabric aircraft. Doped-fabric on an aircraft does not exist in isolation from the surrounding structure but is part of a larger object, and an awareness of the design features beyond just the doped-fabric, therefore, such as how the doped skin might be attached to an underlying framework and the function of this framework is beneficial.

A review of the materials and techniques historically used in constructing doped-fabric is of further use as it provides insights into the problems and challenges experienced by original doped-fabric aircraft designers and users. Such historic problems and challenges may be informative for understanding present day conservation challenges of doped-fabric aircraft, despite the very different function of the aircraft in their present day, static museum context compared to their historic one as dynamic flying machines.

Finally, the historic development and construction of doped-fabric aircraft must be explored so that judgements about the condition of doped-fabric aircraft at the Science Museum can be set within the historical context. From a conservation perspective this historical context is vital since it helps define how and why an object is worth preserving (Chapter 4.1).

The information for this section is drawn from a range of primary archival and literature sources. These include historic scientific journals, government reports, World War I (WWI) military records stored at the National Archives (TNA) in Kew, trade literature and patents. Some details are also based on personal communication with practitioners currently working in aircraft construction, restoration and/or conservation, as well as modern handbooks and guidelines published by national aviation authorities.

2.1. Aircraft Components and Construction Terminology

An aircraft may be broken down into three key sections (Figure 2-1), which are:

- The main body (fuselage and empennage)
- Wings
- Control surfaces

The location of doped-fabric in these various parts of an aircraft will be explored more in the following sections, highlighting when and where it may be a suitable material for construction.



Figure 2-1: Annotated image of a Fokker EIII on display in *Flight* at the Science Museum

2.1.1. Fuselage and Empennage

The fuselage forms the main body of the aircraft and normally contains the cockpit at the front from where the aircraft is controlled. It must be rigid enough to support the wings, tail section and undercarriage both in a static position and during flight. The fuselage may also contain wiring and cabling to connect the cockpit to other areas of the aircraft, as well as space for extra fuel tanks and cargo. The empennage is the tail section of the aircraft where control surfaces important for controlling the aircraft are often located, which will be discussed in more detail in a following section.

There are two main options for building a fuselage (Jakab, 1999; Megson, 2007; Federal Aviation Authority, 2012b). The first type discussed here, called a truss, was typical of most early aircraft. It comprises an internal skeleton which forms a tube and in early designs was often a relatively simple construction of wood, comprising a few poles with diagonal bracing struts or wires for rigidity to prevent twisting or deformation. Truss construction can be found in many of the Science Museum doped-fabric aircraft, such as the Vickers Vimy and

JAP Harding Monoplane (Figure 2-2). Simple and relatively easy to construct, this design has the drawback of tending to become relatively heavy, especially as aircraft size increases, and having poor aerodynamics.

In truss design the skin is not structural as all forces from compression or tension are carried by the framework, which can thus be enclosed in a variety of materials. Doped fabric was therefore common in earlier aircraft for covering the fuselage as it was readily available, though the fuselage might also be left open. Other options explored included plywood sheeting or metal panels though weight considerations could limit their application.



*Figure 2-2: Aircraft fuselages on display in *Flight* made using the truss method. The Vickers Vimy is shown above, the JAP Harding Monoplane below*

The second design option for building a fuselage was a monocoque construction (Figure 2-3). In this form no internal skeleton is needed, and instead the skin itself is a single shell across which the loads are distributed. The lack of an internal framework means a monocoque fuselage can potentially be much lighter and have better aerodynamics than a truss construction, but proves problematic at larger scales when the stresses and forces may cause the skin to fail. Early monocoque designs often proved faster than truss type aircraft, one built by Deperdussin setting a new speed record of 130MPH in 1913 ('The 160 H.P. Deperdussin Racing Monoplane', 1913).

Appropriate material selection for the skin in monocoque structures is vital, one of the earliest used being plywood where the alternating grain directions of the laminate layers help distribute loads evenly across its surface. Doped-fabric, in contrast, was never considered appropriate lacking the stiffness and strength to sustain the necessary loads.

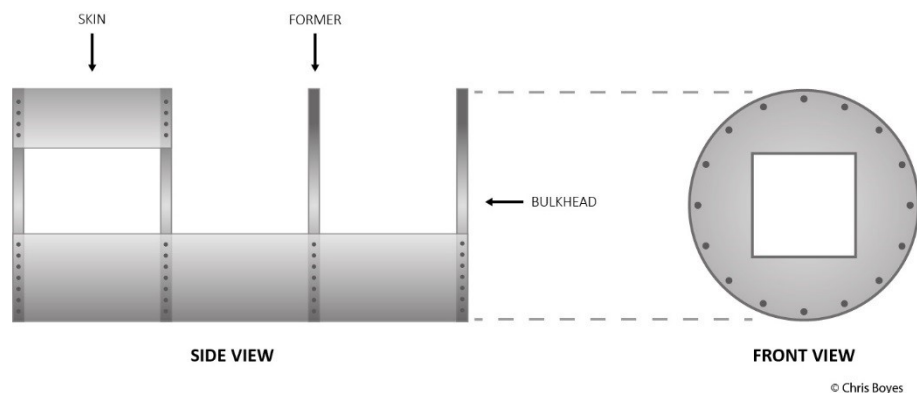


Figure 2-3: Monocoque structure in which the skin itself is load bearing during flight (adapted from (Federal Aviation Authority 2012b, p.9)

A final type of design to emerge is the semi-monocoque, which is a combination of the truss and monocoque (Figure 2-4). This construction is largely based upon the monocoque form, but with additional structural elements, called longerons, which run along the length of the fuselage. The longerons greatly increase the rigidity of the structure and reduce the risk of failure under tensile and compressive loading. Further features used in semi-monocoque designs are stringers, which are shorter versions of longerons in the gap between formers. These have less structural importance than longerons but are important as attachment points for the skin. In the semi-monocoque design, loads are therefore distributed between both the skin of the aircraft and

the internal structure which again means that doped-fabric is generally unsuitable for skinning this type of construction.

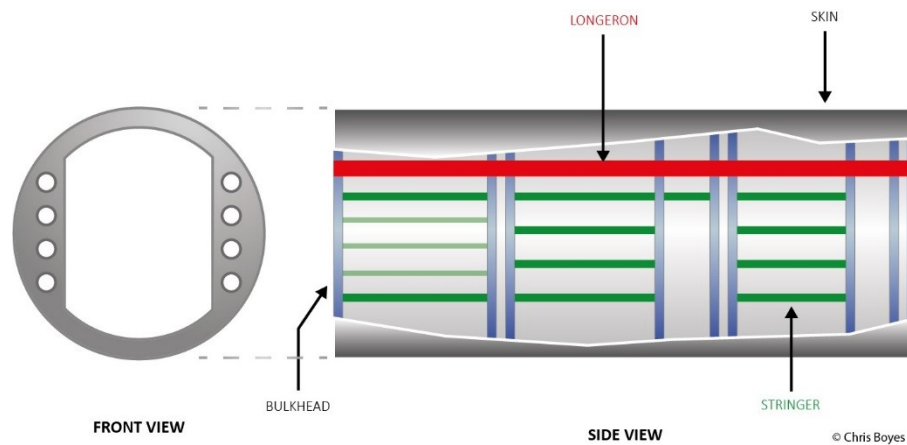


Figure 2-4: Semi-monocoque aircraft construction in which both the skin and internal frame are structural due to the presence of longerons and stringers (adapted from (Federal Aviation Authority, 2012b p.9)

It should be noted, however, that these different materials and construction techniques could be used in combination. The de Havilland Mosquito, for example, a mass produced aircraft during World War II (WWII) is constructed of a plywood shell such as found on monocoque aircraft, but then has a doped-fabric skin applied for its final layer to provide a smooth, protective outer surface (Thirsk, 2008).

2.1.2. Wings

The wings are one of the most distinctive and recognisable features of an aircraft and there are many design options that give each aircraft a distinctive shape, profile and performance attributes. Features that may vary include the size, point of attachment to the fuselage, the dihedral (angle of attachment) and wing shape. The wing structure consists of several key components and sections; the front edge of the wing is known as the leading edge, whilst the rear edge nearest the tail section is the trailing edge. The length of the wing running from the fuselage to the wing tip is the spanwise direction and the direction of wing running from trailing edge to leading edge is known as chordwise (Figure 2-5).

The key components which form the structure of many historic doped-fabric aircraft wings are spars, stringers, ribs and formers. Spars and stringers run spanwise from fuselage to wing tip, whilst ribs and formers are placed

in the chordwise direction. The ribs and formers lack stiffness in their longitudinal directions, so it is common to brace them by tying them together along the length of the structure using rib bracing tape.

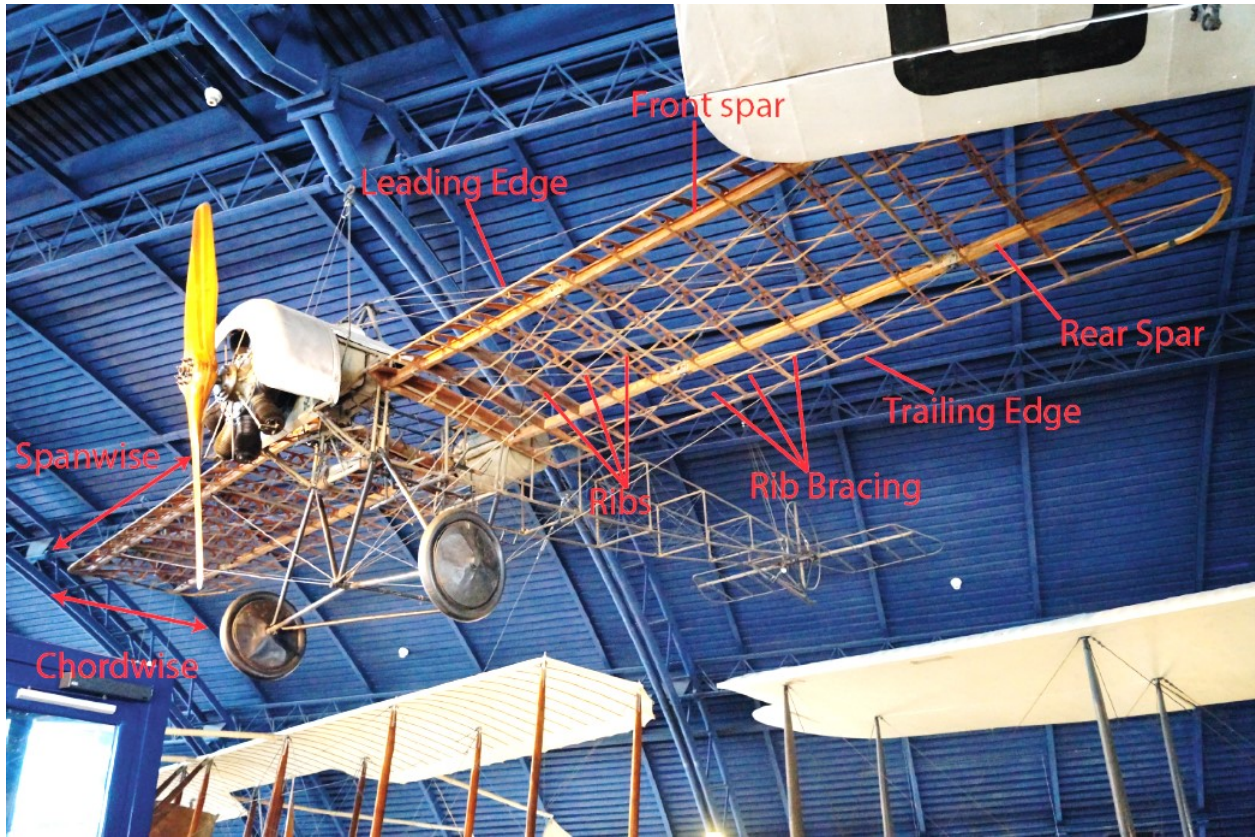


Figure 2-5: Annotated image of the Fokker EIII on display in *Flight* showing the interior frame components used in assembling a doped-fabric skinned wing

There are several different design options as to the shape, size and attachment method for each of these components. In early aircraft wood was the most common material selected, with spruce being preferred for its straight grain, but aluminium became a popular choice in later designs. There are also variations in terms of the number of spars, ribs, and other features that might be used, and their exact positions relative to each other. Wing design may be broken down into the same three broad categories described in the fuselage section, depending upon which elements of the wing are structurally load bearing. These are:

- Truss, in which the load applied to the skin from the air pressure is passed onto the ribs and spars which are the main structural elements.
- Monocoque, where the skin itself is stressed and load bearing, and the interior frame is only for shaping.

- Semi-monocoque, in which there are elements of both a truss and monocoque design, and the load is shared between the skin and internal spars.

The type of wing design is therefore crucial to determining whether doped-fabric is an appropriate and likely material selection for the skin. As with fuselage designs, doped-fabric is a suitable choice for truss type constructions since it does not play a critical role in stiffening the wing structure and the skin need only be sufficiently stiff and strong so as not to deform or fail due to the air pressure flowing over the surface. This resistance to deformation was one of the fundamental reasons for developing doped-fabric, as opposed to using raw, untreated fabric which was found to be too compliant under the air pressures generated during flight and would readily distort which reduced the amount of lift that could be generated. The doped-fabric, however, was not required to add structural strength to the wing itself, since these loads would be borne by the internal truss structure.

For monocoque and semi-monocoque forms, where the skin itself is designed to contribute to the stiffness of the wing structure, the loads involved meant that doped-fabric was an inappropriate choice. Instead, it needed to be replaced by stronger materials, such as aluminium alloys, capable of bearing greater stresses and this adaptation had several key benefits over a doped-fabric, truss construction. One improvement was that the extra space created by the reduction in internal frame components enabled extra fuel storage, and the reduced frame size also meant a better weight to lift ratio.

Further design options are also available to increase the wing stiffness besides the design of the internal framework. Bi-plane and tri-plane structures were developed since the bracing and struts between the layers of wings stiffened the overall structure by increasing its depth. Additional struts could also be run from the fuselage to the wings, again providing extra support and stiffening points. Such interventions come at a cost, however, since these additional structural elements interfere with air flow, increasing the drag and overall weight of the machine.

The presence of such reinforcing design features, such as rigging between wing layers, may also prove significant for doped-fabric conservation since they necessitate the introduction of holes into the doped-fabric skin for the structural elements to pass through. This results in a defect in the doped-fabric skin, a point of weakness where the risk of tearing may be increased as has been observed on aircraft at the Science Museum (Section 3.2.1 discusses the growth of two tears from rigging holes in the wings of the Vickers Vimy).

2.1.3. Control Surfaces

The final area of an aircraft where one might expect to find doped-fabric skins are the control surfaces, which are important for controlling the aircraft during flight. Ailerons, for example, are found in the trailing edge of an aircraft's wings and are important for controlling turning by balancing lift and drag on each side. In addition to ailerons, flaps can be deployed in the wings to alter the wing shape and surface area, whilst the rudder and elevators in the empennage control yaw and pitch, changing the bearing and altitude of the aircraft respectively.

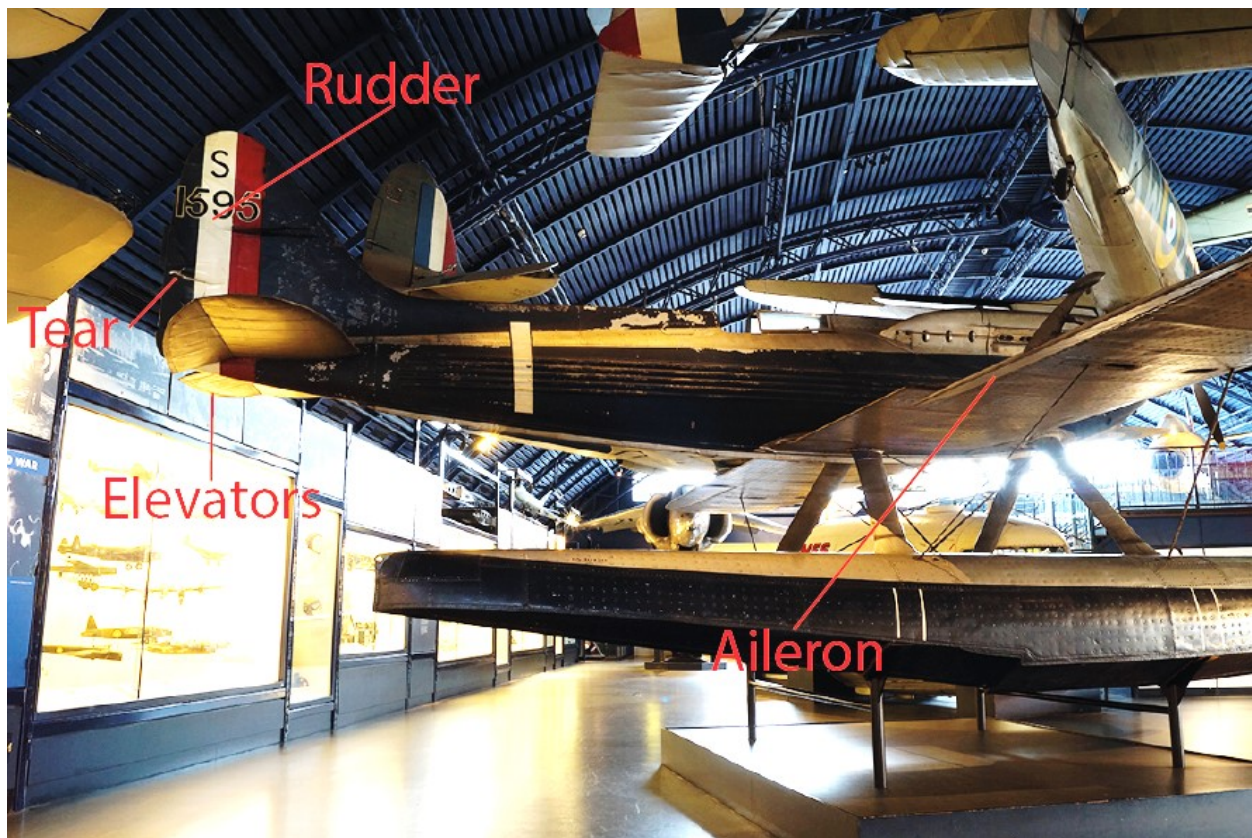


Figure 2-6: The control surfaces of the Supermarine S6B on display in *Flight*

The control surfaces in early aircraft were often made of doped-fabric in much the same way as other parts of aircraft but, whilst later developments in design meant alternative materials such as aluminium began replacing doped-fabric on other parts of aircraft, doped-fabric control surfaces remained in use. This was due to the lightness of the doped-fabric surface compared to a metal skin which mattered because control surfaces were

often manually controlled by the pilots. A lightness of touch and an ability to feel how the surfaces were responding was therefore essential for pilots to have accurate control.

For this reason, it is possible to find doped-fabric surfaces on otherwise all metal aircraft, an example of this within the Science Museum collection is the Supermarine S6B. This aircraft was a revolutionary design when constructed in 1931, incorporating an all metal, stressed skin monocoque fuselage and wings. The rudder, however, is still doped-fabric as evidenced by the tear opening across it and annotated in Figure 2-6.

Identifying the presence of doped-fabric is therefore not always an easy task as it may be in a few, very select areas even on apparently relatively modern, technically advanced aircraft. Without close inspection or knowledge of an aircraft's history or design, vulnerable doped-fabric sections may be overlooked or misinterpreted as metal.

2.2. The Materials Used in Making Doped-Fabric Aircraft

Doped-fabric consists of two fundamental components, a fabric and the dope. This section will discuss the material properties of woven textiles, why these materials were selected and the concerns they were designed to address, the advantages and disadvantages that were experienced in using them, and the alternatives experimented with by manufacturers, researchers and designers. Understanding these factors is important for conservation as it provides a context against which to evaluate the significance and value of the museum objects.

The historic investigations are important, moreover, since they provide a starting point for understanding what materials used in making dopes and which one might expect to encounter on a doped aircraft. Historic research is also revealing of the typical historic observations, problems and concerns that were encountered with doped surfaces. Such information can direct this project by providing a basis from which to develop ideas as to what materials analysis might be appropriate, and in identifying the factors which may be important in dope deterioration.

Table 2-1 provides a summary of the main components of an aircraft and the common materials that might be used in construction of the different areas. Some common trade names and materials identified in the literature have also been included since these often occur in the historic literature in place of the material.

Component Category	Purpose	Material Type	Examples of Trade Names / Manufacturers
Framework	Structural body of the aircraft	Plywood Spruce Aluminium Steel	Duralumin
Fabrics	Provides the flying surfaces for lift and manoeuvrability	Linen Cotton Silk	Madapolam
Dope	Tauten and smooth fabric surface. May also provide some waterproofing	Cellulose Nitrate Cellulose Acetate Cellulose Acetate Butyrate Cellulose Acetate Stearate	Cellon Red Triangle Emallite Blue Star Titanine Emallite Cellon Brittania Novellon Novaria Ascellos Avialine Raftite Nivo (designed for night-time camouflage) Dope 93 (D.93) Dope 94 (D.94)
Varnishes and Coatings	Provides a water coating layer to the dope when applied over the top. May also provide UV protection and radiate heat away from the structure when pigmented or mixed with other additives	Spirit based Oil based	Varnish 114 (V.114) Varnish 84 (V.84) Protective Coating 10 (PC10) Protective Coating 12 (PC12) Pigmented Oil Varnish (P.O.V) Transparent Oil Varnish (T.O.V)
Paint	Markings and camouflage designs		
Solvent Blends	Used to remove dopes and thin them for application		Royal Aircraft Factory 104 (R.A.F. 104) Solvent 33 (S.33) Thinner 36 (T.36)

Table 2-1: A list of aircraft structural elements, their function, the potential materials they may be constructed from and a selection of trade names and products found in the historic literature (Regel et al., 2016)

2.2.1. Woven Fabric Structure, Terminology and Properties

The fundamental component of a woven fabric is the fibre. In the case of cotton and linen fabrics, these fibres are formed primarily of cellulose extracted either from the cotton (*Malvaceae Gossypium*) or flax (*Linum Usitatissimum*) plants respectively (Mather R. R. and Wardman, 2011). To create useful fibres, different extraction methods are required due to the different nature of the plants. Cotton fibres grow around the seeds of the plant and can be picked directly by hand or machine, and cotton fibres also contain a very high proportion of cellulose, approximately 90%, meaning relatively little processing is required to create a usable fibre.

Linen fibres, in contrast, occur within the stem of the plant, which can make extraction more complex. A first step called retting is required, in which the stems are treated to begin breaking down unwanted structures around the cellulose fibres, such as fats, waxes, pectin and hemicellulose. Once this is complete another step known as scutching can occur, during which the stems are broken apart and the fibres extracted. There are various techniques by which these processes can be completed, which can lead to different fibre properties as different proportions of impurities are extracted and longer or shorter linen fibres created.

Once the fibres have been obtained these are processed to create a yarn, the building block of the fabric. To create a yarn the fibres are combined by spinning together so that they join and create a continuous length. The term yarn is in everyday usage inter-changeable with the more common term thread, but is technically slightly different. A thread is a type of yarn which is specifically intended for sewing. The term yarn will be used throughout to avoid duplication of terms.

Yarns can have distinct properties depending upon the qualities of the fibres used and how the yarns are manufactured. Important characteristics include:

- Coarseness (the amount by which individual fibres break the yarn surface)
- Amount of twist and direction (yarns can be twisted in two directions, S and Z)
- Size and shape of the yarn (Yarn cross sections may be elliptical rather than round)
- Number of fibres and density

A woven fabric typically comprises an inter-lacing of yarns in two principal directions lying normal to each other, known as the warp and weft (the weft is sometimes also known as the woof or fill). In the process of weaving, the warp yarns are held under tension and raised or lowered, whilst the weft yarns are passed back and forth between them and each instance of a weft passing over a warp is known as a pick. This creates cross-over points between the warp and weft directions, where the yarns in the two directions are in contact. The frictional force

exerted between yarns where they are in contact is important for holding the yarns in place within the structure.

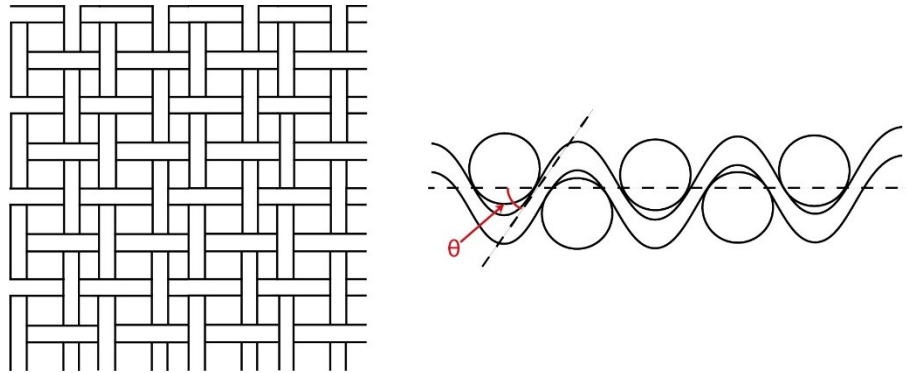


Figure 2-7: Structure of a plain weave fabric (left) and its cross section (right) with the crimp angle, θ , labelled.

Different weave patterns may be created by altering the number of warp threads the weft passes over and under. In a plain weave, the weft alternates with each successive warp thread, passing over, then under, then over and so on. Other types of weaves include twills, where a ribbed pattern is created, and satins (or sateens), in which a warp or weft ‘floats’ over four or more of their counterparts. These different patterns can be used to impart different properties, for example a satin weave generally results in a fabric with a high lustre since the high float number results in a more even surface and less scattering of light from it.

The density and weight of the fabric may be manipulated by changing the number of warp and weft yarns. This is measured by the number of warp and weft threads for a given unit of material. Open weaves describe a fabric having fewer yarns per unit, such that gaps within the weave structure are visible, whilst close packed weaves have very densely packed yarns so that no gaps are visible, though the distinction between the two is not always very well defined.

Once weaving is complete further finishing processes may be applied to a fabric. Calendering, for example, is applied when a fabric is passed between heated rollers. This flattens loose fibres creating smoother, more lustrous finishes. Other processes include bleaching, in which the fabric is chemically treated to alter its colour, and sizing in which a coating is applied which may change certain properties of the fabric, such as its water resistance and surface texture.

The weaving process gives rise to several important characteristics of woven fabrics. One factor is known as the crimp. This is the relative angle through which warp and weft yarns are diverted from the straight-line path to pass over and around each other. The crimp factor is related to several further fabric properties, such as fabric extensibility and the amount of friction at yarn crossing points, and may lead to anisotropic properties between the warp and weft.

Young and Hibberd demonstrated how crimp influences the mechanical properties of fabrics at low extensions, causing a non-linear extension pattern under elastic loading (Young and Hibberd, 1999). This is because under initial loading conditions of a fabric, rather than extension on the micro-scale of the cellulose molecules, there is extension at the macro level as the crimped yarns straighten out. Eventually friction between yarns increases so that they lock into position, at which point the cellulose molecules extend on a molecular level and a linear relationship between strain and load is observed.

They also demonstrated that the warp generally has a lower stiffness and greater extensibility than the weft, and that this is likely a result of the weaving process. As the warp is raised and lowered to allow the weft to pass through, it must pass through a larger distance, and so has a greater crimp. There is therefore more compliance in this direction in general, due to the extra crimp extension.

The study also found that the loading conditions matter as under uniaxial loading, in which samples were only extended in the warp or weft direction, as a reduction in crimp occurred in the loaded direction there was a simultaneous increase in crimp in the non-loaded direction. This was measured as a contraction in the un-loaded direction analogous to a poisson's ratio effect. This occurred as the unrestrained yarns in the non-loaded direction had to pass through the increased path length around the straitening yarns in the loaded direction. Under biaxial loading, the effects of this crimp exchange were lessened compared to in uniaxial loading as both directions were loaded. This difference in the exchange of crimp factor results in the same material appearing to be stiffer under biaxial conditions than when measured under uniaxial testing as the crimp exchange that can occur, and hence re-ordering of the weave, is restricted.

Hysteresis was also detected during cyclic loading in both warp and weft, and uniaxial and biaxial measurements and was attributed to friction at the contact points between warp and weft fibres altering the rate at which tension increased, compared to when the sample was unloaded.

With so many variables, from the initial production of fibres through to the finished woven fabric, predicting the bulk mechanical properties of a product made from cellulosic yarns is a difficult process. Even measuring basic properties of the individual fibres forming a yarn poses a technical challenge since the fibre cross-sections are

not necessarily round as might be assumed, and so calculations of stress were hindered before Scanning Electron Microscopy (SEM) enabled imaging of the fibre ends. Mechanical properties, moreover, can vary since even the growing conditions, let alone subsequent processing, may influence the development of plant structures, leading to a different product between harvests and locations.

This issue of determining the cross-sectional area of a sample becomes even more complex with a woven structure, as the pressure exerted by warp and weft upon each other change their respective shapes depending upon the compressibility of the yarn used, which in turn alters the amount of surface area contact between warp and weft. Calculation of stress for woven fabrics is thus problematic, since the cross-sectional area of a piece of fabric is likely to change considerably during testing as the forces exerted by warp and weft change, and points of contact between yarns shift. For this reason, the studies of woven fabric and those in the next section on paintings more often report the load or load per sample width, rather than load per cross-sectional area, i.e. stress.

The complex nature of woven structures has also been a problem in developing theoretical models for the behaviour of woven materials for predicting deformation under load. Early models made a number of assumptions, such as that the yarns acted as perfect, incompressible cylinders and ignored interaction between yarns (Kawabata, Niwa and Kawai, 1973). Later studies have attempted to refine this, for example by introducing yarn interaction components, such as compressibility factors for the yarns when coming into contact with each other (Tan, Tong and Steven, 1997).

2.2.2. Fabric Selection

Numerous research projects were conducted during the early years of aviation into the mechanical and physical properties of different fabrics. Many of these projects were undertaken by government institutions, such as the Royal Aircraft Factory in Great Britain, the National Advisory Committee for Aeronautics (NACA) in the USA and the German Experimental Institute for Aviation. The main aim of these projects was to establish the best type of fabric to use based on characters such as their extensibility, tensile strength and durability.

The development of doped-fabric aircraft pre-dates the creation of synthetic textiles such as Ceconite, a heat shrunk polyester fabric, which may now be used on modern fabric aircraft (Goldenbaum, 2008). Research from the 1910's onwards therefore focused around organic, cellulosic materials, the two main options being linen and cotton. Alternatives included silk and ramie but none of these appear to have been developed to any great extent due to a combination of other factors, such as cost, availability and susceptibility to deterioration.

Indeed, the importance of economic and social factors, such as the cost and means of production, which go beyond purely 'material' properties, are critical (Remington, 1919). The literature indicates, for example, that Irish Linen was generally a preferred option in the United Kingdom, whilst the USA preferred cotton due to the ready availability of these materials in their respective markets (Walen, 1918; Catoe, 1962). The use of cotton and linen will be considered in more detail here since they appear to have been the most commonly used materials in aircraft construction.

The tensile strength and mechanical properties of different types of fabric to ripping and tearing was of concern, since this was taken as a measure of whether fabric would fail in flight. Walen (Walen, 1918) and Esselen Jr (Esselen, Jr., 1918) both report that within the UK there was a general prejudice against using cotton as tensile test results indicated it had a lower tensile strength compared to linen when tested to failure. Research at The Royal Aircraft Establishment also appears to have reached the same conclusions (Turner, 1920).

Other tests, however, which involved ripping and bursting the woven fabric through application of pressure to the surface, rather than tensile loading, were argued to be more representative of the actual loading exerted on a fabric skin during flight. These tests indicated that cotton could withstand greater loads than linen in this context, so could prove a more suitable substrate for a doped-fabric (Walen, 1920).

The greater loading of cotton under this type of loading was attributed to its greater extensibility, which meant it deformed more before failure (Walen, 1920; Ramsbottom, 1924). This extensibility was valued as it meant that cotton fabric would be less likely to fail as the air frame it surrounded moved during flight, alternately stretching and compressing the skin in different areas. Such benefits could also prove problematic, however, as an overly extensible material could result in significant deformation of the skin and cause distortion and fouling of the air flow (Pröll, 1921, 1924).

A further material, known as mercerised cotton, also received consideration, which is a derivative of cotton made by swelling cotton yarns in an alkaline solution. Modern studies have suggested that mercerisation results in a change in the conformation of the cellulose molecules, reducing the overall order of the cellulose crystalline structure but increasing the amount of hydrogen-bonding between the molecular chains (Wertz, Bédoué and Mercier, 2010).

Historic studies for aircraft production were primarily interested in how mercerisation influenced the physical properties of fabrics rather than their chemistry, and reported that mercerised cotton had a comparable, if not greater tensile strength than linen, whilst still retaining much of the extensibility of un-mercerised cotton (Walen, 1920). Mercerised cotton was therefore recommended as preferable to other forms of cotton. Other studies,

however, found that the changes in tensile strength on mercerisation were highly dependent upon the exact conditions and processes used during the mercerisation process, such as temperature and whether the fabric was held under tension, and so care was still required in choosing an appropriate material (Wilkie, 1933).

The findings above, moreover, should only be treated as generalisations, due to the many variables which go into producing the properties of a finished, woven textile (See chapter 2.2.1 for more details on the properties of a woven material). There are a huge number of variables involved in the production of a woven textile, from the selection and extraction of fibres, through to how these are then processed to form yarns that are then woven together into a textile which may then receive further finishing treatments; all of which makes modelling and predicting a textiles properties extremely complex (Walen, 1920; Kawabata, Niwa and Kawai, 1973; Tan, Tong and Steven, 1997). The amount of potential variation is consequently almost limitless, with differences in the choice of material being only one aspect in the properties of the final product.

These variations are important as they influence not only the individual properties of the finished woven fabric, but also alter how the fabric interacts with the dope. Researchers and developers of doped-fabric were aware that, whilst the properties of the fabric on its own in terms of strength and extensibility were of interest, what was also of great importance was how it would ultimately interact with the dope to create the final composite doped-fabric.

The type of weave generally recommended, for example, was influenced by the fabric interaction with the dope. Plain weave, the simplest woven fabric available in which yarns are woven over and under each other consecutively, appears to have been the standard format for aircraft textiles as it was believed the dope restricted movement of the weave pattern (Turner, 1920). Choosing a more time consuming, expensive, and complex weave pattern, therefore, was assumed to confer very little advantage to the final doped-fabric and so were best avoided.

Other properties which were also found to have an impact on the interaction of fabric and dope included the fibre coarseness and the type of finishing process applied to the fabrics, which was linked to the penetration of the dope (Ramsbottom, 1924). Sizes and finishes, for example, might be applied to fabrics further changing their response to moisture and performance when combined with dope. It was generally recommended therefore that un-sized fabrics should be used, and that any sizing present on a fabric be removed to avoid interference with the penetration of dope into the fibre.

Besides strength and dope interaction, the reaction of fabrics to Relative Humidity (RH) was also of interest to early researchers as aircraft were expected to experience significant and rapid fluctuation in RH during flight. It was understood that fabrics swelled and shortened with high RH, and that this could influence the tensile

properties of the material (Urquhart, 1923). As with other material properties, the fibre processing was found to be crucial, the extent and rate of change in mechanical properties being highly dependent upon the type of yarn used and how it had been transformed into a woven fabric (Urquhart, 1927; Kline, 1935b).

Finally, any consideration of aircraft materials must take account of the issue of weight. Any material which was deemed too heavy would simply be ruled out of contention for use as an aircraft skin and limiting the weight of the fabric was therefore critical. Reducing the density of the weave, therefore, i.e. the number of yarns in a given area, was considered desirable by aircraft designers, but this could result in reductions in strength and load bearing capacity if overdone.

The range of woven textile products available to aircraft manufacturers was consequently extremely large, all of which could provide different benefits and disadvantages to the aircraft's performance. This is perhaps why both Irish Linen and cotton, and later mercerised cotton, were used without one ever being generally acknowledged as the objectively correct choice across all times and locations. A definitive statement as to which fabric was 'better' was impossible to provide as different researchers, institutions and bodies recommended different materials and processes depending upon a complex range of social, economic and technological considerations.

Indeed, what was perhaps most important to manufacturers was the reliability of the aircraft fabric and a trust in the fact that whilst different products might vary in certain respects, they all met basic criteria which made them suitable for use as an aircraft skin. To this end, as aircraft manufacturing became more organised and widespread, standards were published regarding the quality and types of fabric to be used, especially for military applications (Turner, 1920). Table 2-2 provides details of the standards set out for mercerised cotton by the British military during WWI. No details of a linen specification were found in the archival literature, but details of an aircraft linen supplied by Aerospace Ltd purportedly to a historic British standard 9F1 are provided for comparison.

Standard	Yarn Twists (Twists/inch)	Preparation	Sizing	Warp threads /inch	Weft threads /inch	Weight (oz/sq yd)	Minimum Strength (lbs/inch)
British Mercerised Cotton Aeroplane Fabric (Grade I.): 3F.8 (BESA, no date)	Single 28-34 Double 15-17	Mercerise under tension and ensure a neutral pH finish	Use unsized threads if possible. If not, only size with tallow, palm oil or Japan Wax free from paraffin oil. Max 3.5% sizing content.	80	84	4.5	80
LAS Aerospace 9F1 Irish Linen (Arville Textiles Ltd., no date)		Calendered		74	76	4.37	Warp: 69 Weft: 80

Table 2-2: Two fabric specifications recommended for use in the construction of doped-fabric aircraft

The extent to which such standards were followed and applied, however, is not established. The production and availability of fabric products that met such standards may have been variable, especially during times of stress such as war time when aircraft production rose rapidly against a backdrop of restricted supply chains (Ollerenshaw, 1999). The existence of standards, therefore, should not be taken as a guarantee that fabrics meeting these specifications were definitely used to make every single plane, but as useful indicators as to the general quality and type of fabric considered appropriate for use in aircraft manufacture.

2.2.3. Dope Development and Formulations

A substantial amount of research was undertaken into the behaviours of dope during the first half of the twentieth century to improve dope recipes. There were numerous commercial manufacturers of dope, each of whom produced different formulations and products which might provide slightly different properties and results. A summary of dope formulations found in the historic literature is provided in Table 2-3. The range in formulations was in part because the requirements and expectations of what made a good dope varied between individuals and organisations, and changed over time. There are, however, several clear trends as to the types of materials and techniques preferred for preparing dopes, and the features which were considered important.

Dope Name	Source	Base Tautener	Base (g)	Plasticiser	Plasticiser Quantity (g)	Solvents	Solvent Quantity (ml)	Additives	Additive Quantity (g)
British Emailite Company	The British Emailite Company Ltd. 1919	Cellulose Acetate	100	Triphenyl Phosphate	8.57	Acetone	1,214		
				Acetanilide	12.86	Triacetin	14		
British Emailite Company	The British Emailite Company Ltd. 1919	Cellulose Acetate	100	Triphenyl Phosphate	14.29	Methyl Acetone ^a	476		
				Acetanilide	23.81	Methyl ethyl ketone	714		
British Emailite Company	The British Emailite Company Ltd. 1919	Cellulose Acetate	100	Triphenyl Phosphate	13.64	Methyl Acetone ^a	682		
				Acetanilide	22.73	Methyl ethyl ketone	114		
						Benzol*	341		
						Triacetin	14		
British Emailite Company*	The British Emailite Company Ltd. 1919	Cellulose Acetate	100	Triphenyl Phosphate	12.86	Methyl Acetone ^a	476		
				Acetanilide	47.62	Methyl ethyl ketone	714		
						Triacetin	38		
British Standard Reference Dope 1918	British Engineering Standards Association 1918	Cellulose Acetate	100	Triphenyl Phosphate	15.15	Acetone	758		
						Benzol	364		
						Alcohol (Industrial Spirit)	364		
						Benzyl Alcohol (C ₆ H ₅ CH ₂ OH)	30		

Dope Name	Source	Base Tautener	Base (g)	Plasticiser	Plasticiser Quantity (g)	Solvents	Solvent Quantity (ml)	Additives	Additive Quantity (g)
Reference Protective Covering	British Engineering Standards Association 1918	Nitro-cellulose Syrup	100	Castor Oil	22.41	Butyl Acetate	65	Yellow Ochre	65
						Alcohol (Industrial Spirit)	6	Carbon black	0.26
						Benzol (Benzene)	65		
						Acetone	86		
Nitro-cellulose Syrup	British Engineering Standards Association 1918	Cellulose Nitrate	100			Butyl Acetate	397		
						Denatured Alcohol	63		
Acaroid Resin^	Dreyfus 1924	Cellulose Acetate	100			Acetone	316	Acaroid Resin	100
Acaroid Resin ^	Dreyfus 1924	Cellulose Acetate	100			Acetone	1,896	Acaroid Resin	200
Fire Retarding Dope	Flatters 1919	Casein	100	Gelatine	100.00	Water	2,004	Borax	50
								Neutral Soap	50
								Best Glue	100
								Oil mulch	50
								Soluble Creosote	6
United States Navy Dope	Grossman & Haven 1944	Cellulose Acetate Butyrate	100	Triphenyl Phosphate	11.11	Diacetone Alcohol	160	Carbon black	21
						Ethyl Acetate	390		
						Toluene	231		
						Acetone	379		

Dope Name	Source	Base Tautener	Base (g)	Plasticiser	Plasticiser Quantity (g)	Solvents	Solvent Quantity (ml)	Additives	Additive Quantity (g)
A 'common solution'	Inoue 1941a	Cellulose Acetate	100			Acetone	759		
						Methyl ethyl ketone	166		
						benzene	127		
						Toluene	64		
						Alcohol (Industrial Spirit)	42		
						Ethyl lactate	43		
A 'common solution'	Inoue 1941a	Cellulose Nitrate	100			Ethyl Acetate	557		
						benzene	143		
						toluene	216		
						Butyl Acetate	354		
						Ethyl lactate	70		
						Butyl glycol	38		
Adapted British Standard Dope	Kline 1935a	Cellulose acetate	100	Triphenyl Phosphate	15.49	Acetone	833		
						Ethyl Acetate	314		
						Denatured Alcohol	357		
						Ethyl lactate	68		
Dope Example I	Societe Nauton Freres et de Marsac & Tesse 1919	Cellulose Acetate	100			Acetone/ Methyl Acetone	1,053		
						Ethanol/ methanol	176		
						Benzyl Alcohol	43		
						Benzol cristallisable (benzene?)	159		
						Eugenol/ butylphenol	3		

Dope Name	Source	Base Tautener	Base (g)	Plasticiser	Plasticiser Quantity (g)	Solvents	Solvent Quantity (ml)	Additives	Additive Quantity (g)
Dope Example II	Societe Nauton Freres et de Marsac & Tesse 1919	Cellulose Acetate	100	Butyl tartrate/ Diethyl phthalate	33.33	Acetone/ Methyl Acetone	955	Zinc Oxide/ Lithopone (Barium sulphate and zinc sulphide)/	22
						Ethanol/ methanol	176	Aluminium 'en paillettes' (powder?)	17
						Benzyl Alcohol	27		
						Benzol cristallisable (benzene?)	159		
Dope Example III	Societe Nauton Freres et de Marsac & Tesse 1919	Cellulose Acetate	100			Acetone/ Methyl Acetone	1,054		
						Ethanol/ methanol	176		
						Benzyl Alcohol	43		
						Benzol cristallisable (benzene?)	159		
						Eugenol/ butylphenol	7		
Fire Retarding Dope	Sutherland 1919	Acetyl Cellulose	100			Acetone	927	Boric acid	40
						Benzol	868		
						Benzyl alcohol	32		

Dope Name	Source	Base Tautener	Base (g)	Plasticiser	Plasticiser Quantity (g)	Solvents	Solvent Quantity (ml)	Additives	Additive Quantity (g)
Fire Retarding Dope	Sutherland 1919	Acetyl Cellulose	100			Acetone	237	Boric acid	20
						Benzol*	442		
						Benzyl alcohol	24		

Table 2-3: A list of selected dope formulations found in the historic literature. Quantities have been normalised to the base tautening agent, usually a cellulose ester.

α Methyl acetone is described as a mix of acetone, methyl alcohol and methyl acetate

** Benzol could refer to benzole, a benzene and toluene mix, or benzene.*

+ This was noted to be a slacker dope

^ Acaroid resin may refer to a resin such as shellac though the exact ingredient intended is unclear

When considering the development of dope, it is important to understand the reasoning behind doping, as this informs the qualities and characteristics as to what defines a good dope. As discussed, a key property of the dope is its ability to shrink a fabric and make it taut. This was found to increase the stiffness of the doped-fabric composite, reducing the amount it deformed due to air pressure. Beyond this, however, if not equally important was the ability of the doped-fabric to retain this stiffness during use, as exposure to increased RH and aging of the material was found to cause notable relaxation and slackening of doped-fabric skins.

Other qualities desired of a dope included fire resistance as this was a significant danger during early flight when crashes were common and the heat from engines or even direct sunlight could be enough to start a conflagration. Dope might also be applied as a protective barrier to lengthen the lifespan of the expensive fabric substrate. A summary of potential functions of dope are provided in Table 2-4.

Requirement	Purpose	Key Components Responsible in Doped-Fabrics	Examples of Materials Used
Tautness	To create a smooth flight surface which could withstand the pressures generated during flight.	Polymer used for plastic film formation	Cellulose esters
Fire-retardant	Health and Safety	Polymer used for plastic film formation Fire suppressing additives	Cellulose esters Metal salts
Light weight	To improve, or even enable, flying ability of aeroplane	Polymer used for plastic film formation	Cellulose esters
Tensile Strength	To prevent wing failure during flight	Fabric substrate Polymer used for film formation	Irish Linen or Cotton Cellulose esters
Environmental protection	To extend the life of the doped-fabric as far as possible against climatic conditions such as sunlight and moisture	Powdered metals and pigments Plasticisers	Aluminium powder, yellow ochre, carbon black Triphenyl phosphate
Camouflage	To decrease visibility from above and below	Coloured pigments added to the final dope coatings.	Carbon black, yellow ochre

Table 2-4: A list of the required properties and related component of dope (Regel *et al.*, 2016)

The above table captures the main concerns, but it should be noted that novel dopes and theories were also being developed and tested, though with varying levels of success. There were efforts, for example, to invent an anti-icing dope, a pre-doped fabric which could be shrunk once attached to the aircraft (much like modern synthetic versions available now), and even an invisible plane by using a very fine fabric sandwiched between layers of cellulose acetate sheets (British Emallite Company Ltd., 1915; Clay, 1924; Palmer, 1929). None of these ideas seems to have ever become mainstream.

A common test method to evaluate how dopes performed was to coat panels of fabric with the dope, and then expose them to the outdoor weather, or to receive pieces of fabric from aircraft in use to check their performance. This approach does have merit given that the main concern of researchers was to study how dopes behaved in real world conditions, but does make repeatability and the effect of different variables difficult to separate. There were attempts at more controlled test conditions, but it seems that such efforts are rare. Methods of measuring the tautness of a fabric panel also varied, and several institutions developed their own individual testing apparatus, and so again comparison or use of quantitative data is limited (Palmer, 1929; Kline and Schiefer, 1939).

The Tautening Component of Dope

Since tautening is the most important role of dopes, it is not surprising that this is the area where most researchers tended to focus. The major problem researchers were attempting to solve was that not only did they need to find a material that would tauten a fabric when first applied, but which would continue to hold the fabric taut and not slacken when exposed to environmental conditions, particularly high levels of Relative Humidity (RH). Early efforts to create a taut surface had used rubberised fabrics, and a variety of other common, readily available materials, such as casein, starch paste and proteinaceous glues as coatings. None of these were found to be very effective, however, and were quickly abandoned (Flatters, 1919; Smith, 1919; Drinker, 1921).

Subsequently a family of materials based on cellulose esters, into which considerable research and manufacturing experience had already been established began to be investigated and experimented with for use in aircraft dopes (Worden, 1911, 1916). In the years before World War I, cellulose nitrate was found to act as an effective tautening agent. Cellulose nitrate (Figure 2-8) soon became a standard material for use in dopes and investigations right through to the 1940's consistently found cellulose nitrate to be not only one of the best tautening materials, but also one of the most resistant to slackening on exposure to increased RH (Kline and Malmberg, 1938; Reinhart and Kline, 1939; Inoue, 1941b). This combination of factors meant that cellulose nitrate proved an extremely popular choice for making dopes, and nitrate based dopes are still commercially available today.

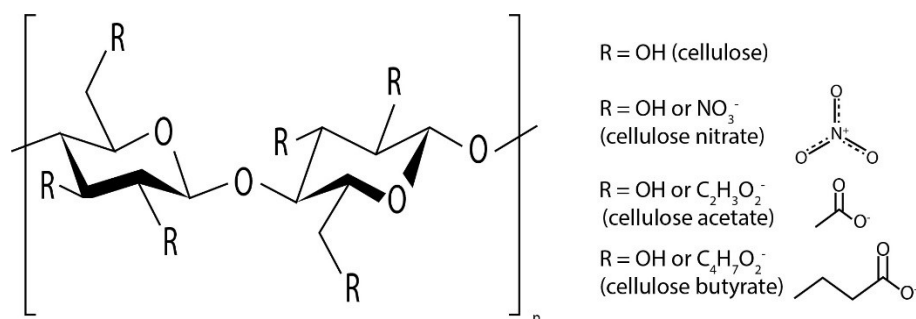


Figure 2-8: The chemical structure of cellulose and the various cellulose derivatives commonly used as a tautening agent in making dopes

The major drawback from using cellulose nitrate in dopes, however, was that they were highly inflammable, and problems with fire were common in aeronautics and other industries dependent on the material, such as cinematography. The stability of cellulose nitrate is related to the number and position of nitrate groups substituted onto the cellulose chain and, in its fully nitrated form is a potential component for explosives.

Given these problems, trials were carried out to try and find potential additives to reduce the instability of nitrate dopes and a number of solutions were proposed (Bradley, 1919; Ward and Fletcher, 1925; Hughes, 1926). One suggestion recommended in several papers and patents was to add a mix of boric acid and borax into the dope to reduce its flammability, a material which is still being investigated as a potential fire retardant (Sutherland and Wall Paper Manufacturers Ltd., 1919; Hughes, 1926; Kline, 1935a; Weissberg and Kline, 1949; LeVan and Tran, 1990; Akarslan, 2015). Assumptions should not be drawn, however, about whether a fire suppressant may have been added to a dope and what it might be, as no common approach seems to have developed.

This is because rather than attempting to further adapt cellulose nitrate for use, researchers also considered alternative materials and cellulose acetate became a standard alternative. Cellulose acetate was already known to be a much safer option from the movie industry, where it was known as safety film and replaced cellulose nitrate as the most common material for making film reels. In Great Britain, cellulose acetate became the preferred dope for military purposes by the middle of WWI, and was recommended for use on all front-line planes by 1917 ('Deputy Director of Equipment Communique to Airboard Office 26th October 1917', 1917).

There were drawbacks, however, to replacing cellulose nitrate. Cellulose acetate was generally found to have inferior tautening properties and poorer performance in weathering tests, which had to be set against its lower flammability and is likely attributable to the more hydrophilic nature of the acetal groups compared to that of nitrate ones (Palmer, 1927). There were also issues with supply, especially during WWI when Britain's only

suppliers during the early phases of the war were based on the continent before factories could be built in the UK (*New York Times*, 1918; *Communique Aviation Militaire Anglais SE., to ASMA War Office 23/11/15*, 2015; Coleman, 1975). Even outside of wartime, supply issues could be problematic as after WWI demand for cellulose acetate slumped making production uneconomical, resulting in a drop of production and further supply problems ('The Finishing Touch: Cellon Celebrate 40th Anniversary', 1951).

The quality and characteristics of the dope product being produced and supplied were consequently probably variable (Bagnall-Wild, 1917). Quartermaster reports during WWI state that some batches of dope received had already turned a yellow brown colour, and were emitting a strong vinegar odour (*Communique from Director of Aircraft and Quarter Master General to D.A.E War Office 6th June*, 1916). This suggests that the dope being supplied was in certain cases highly degraded and unsuitable for use before even being applied to the aircraft, despite specifications from the British Engineering Standards Association regarding the quality of raw materials to be used in terms of their material qualities, such as acidity and viscosity (British Engineering Standards Association 1918).

There were further developments in the tautening materials used during the 1930's, when references to cellulose acetate butyrate appear in the literature, especially in relation to studies being conducted in the USA. This material belongs to the same family of cellulose esters as cellulose nitrate and cellulose acetate. It was considered a reasonable compromise having nearly as much tautening strength as cellulose nitrate, with almost as low a flammability as cellulose acetate (Kline and Malmberg, 1938; Meyer and Gearhart, 1944; Weissberg and Kline, 1949). Cellulose acetate butyrate seems to have become the dope of choice for most applications, and this dope is still readily available from modern suppliers.

A final material proposed to act as the main tautening agent was cellulose stearate (Jones and Hockney, 1944; Dreyfus, 1949). This seems to have been developed too late in the life time of doped-fabric aircrafts to receive significant interest or be widely used, though it was suggested that its tautening was as good as cellulose nitrate, with the benefits of low flammability and improved film flexibility.

Dope as a Protective Coating

Besides the tautening power of dopes, their potential to act as a protective barrier for the fabric substrate became an important property. Using dope for protection made sense as the fabric skin was expensive and time consuming to replace, whereas dope could be removed relatively economically with solvents before being reapplied. Dope was consequently not considered a long-term material but was expected to degrade, and studies recommended

it be replaced approximately every 60-90 days (Esselen, Jr., 1918). During its more limited lifetime, therefore, the dope was expected to undertake several functions to help prolong the more precious fabric beneath.

A key feature of dope was its waterproofing behaviour. This was vital for extending the life time of the fabric as it helped prevent moisture penetrating into the fabric, thus causing it to relax and lose its tautness over repeated cycles. For dope to be effective, therefore, it needed to form a continuous film over the fabric and be sufficiently flexible to prevent the formation of micro-cracks where water could penetrate. There are a range of factors which can influence the film formation and flexibility of a dope film. One variable is the blend of solvent used to dissolve the cellulose ester of choice and any other additives for application, and historic dope manufacturers attempted to manipulate solvent mixtures to control the final film properties.

Low volatile solvents and additives, such as tetrachloroethane (TCE) and triacetin were used as it was believed that traces of these remained trapped in the film, plasticising it and preventing it from becoming brittle (Royal Aircraft Factory, 1915; Goldsmith and British Emailite Company Ltd., 1919). These slower evaporating solvents also prevented over-rapid drying of the film, which could result in fast shrinkage and cracking.

Another technique to prevent films from cracking was to introduce plasticisers. Plasticisers are additives specifically intended to lubricate the film by embedding themselves between polymer chains, thus interfering in the attraction between polymer molecules. Numerous types were tested, though tri-phenyl phosphate appears to have been widely adopted (Sutherland and Wall Paper Manufacturers Ltd., 1919; Lester, 1943). The proportion of plasticiser was also important, since too much could result in an overly extensible film, leading Reinhart and Kline (Reinhart and Kline, 1939) to recommend no more than 10-20% be added. There were, however, other potential plasticisers, such as castor oil, and variation was possible.

The penetration of moisture into the fabric was also of concern due to the risk of biological growth, such as mould, which could begin to digest and thus weaken the organic material. One anti-fungal type dope currently commercially available from LAS Aerospace is that of a red dope containing iron oxide, which is applied in the first few coats of dope. The earliest reference to a red, iron oxide containing dope found in the archive material was to one made in 1922, though it could not be established how wide spread the practice was or if and when it became a standard treatment (*Report No. H.C. 758: Report on the Chemical Examination of Deteriorated Pigmented Acetyl Dope from India*, 1923). This dope type has the added benefit of being coloured red due to the iron oxide, making it easier to see which areas have been worked when applying it as a first coat.

Dopes were also developed for protection from Ultra Violet (UV) radiation as it had been established that exposure to high levels of sun light increased rates of deterioration in cellulosic fabrics (Atkins and Woodcock, 1917; Wendt,

1922; Ramsbottom, 1924; Glendinning, 1926b). Pigmenting the dopes or adding metal powders, such as aluminium, were found to be effective ways of preventing UV penetrating to the fabric below (British Engineering Standards Association, 1918). The addition of aluminium was also found to have the additional benefit of radiating heat away from the internal frame, which reduced warping of wooden structures (Ramsbottom and Newton, 1917; Royal Aircraft Factory, 1917b). Concerns about weight meant that pigmented or aluminium containing layers would be used only for the very last top coats, with several layers of clear dope underneath.

The effect of UV on the dope, however, was discovered to have unexpected side effects. TCE, although believed a very useful solvent for increasing film plasticity, was also suspected of causing fabrics to deteriorate at an accelerated rate as historic reviews found it released acidic compounds when exposed to UV which would then chemically react with the fabric (Royal Aircraft Factory, 1915; Robertson, 1916). This, coupled with the fact that it was highly toxic and linked to several fatalities in aircraft manufacturing, led to it being banned from British dope formulations in 1917 at which time substitutes had to be found (British Emallite Company Ltd., 1917; Hamilton, 1918). The effect of acidity on fibre strength was also of interest to Barr and Hadfield who studied the effect of sulphuric acid on textiles (Barr and Hadfield, 1918).

Some researchers suspected, however, that it was not only TCE that had deleterious effects on doped-fabric, and certain cellulose acetate doped-fabrics were noted by Glendinning as susceptible to deterioration even when not exposed to sunlight. He suggested that this could be due to the release of degradation products from constituents of the dope, and tested this by exposing linen fibres to a range of chemicals, including tri-phenyl phosphate, benzyl alcohol, castor and amyl acetate and then testing their tensile strength to judge whether deterioration had occurred (Glendinning, 1926a). Glendinning ultimately concluded, however, that unless the fibres were kept in a sealed environment, exposure to the individual constituents was not a problem.

It should be noted that dopes only seem to be developed for use as a protective coating in Great Britain during WWI. Before this point, varnishes and paints taken straight from use as boat and carriage varnishes were applied over the dope layer to provide protection (*Report 84/F Doping of Aircraft*, 1914). More specialised varnishes, both pigmented and containing aluminium powder, were developed throughout WWI for this purpose before the formulation of specially designed dopes began to render them obsolete. The use of such other protective coatings over the dope, however, may have carried on for some time, and studies of doped aircraft should be aware of the potential use of such materials.

2.3. Constructing and Maintaining a Doped-Fabric Flight Surface

As the preceding discussion demonstrates, doped-fabric surfaces may be found in various locations of an aircraft but that it was not a structural element for stiffening the aircraft structure. It still had to be able to resist deformation due to the pressure of airflow during flight, however, and provide a smooth, even surface to limit drag. The method of attachment of doped-fabric is consequently important and may have important consequences within the museum context, determining where failures occur and how conservation treatments in one section may impact the object as a whole.

2.3.1. Securing the Fabric

Where the width of a fabric roll is wide enough to cover the whole of the upper or lower wing surface, it is recommended that only two pieces of fabric are sewn together with the seams running spanwise along the length of the trailing and leading edges. This results in two main seams running the length of the wing, but none in the chordwise direction along the direction of the ribs (Figure 2-9). Guidelines depending upon the specific build context are provided as to what types of stitching should be used and how seams should be prepared to ensure that there is sufficient overlap of fabric sections and that stitching is sufficiently strong (Federal Aviation Authority, 2012a).

Where fabric is not wide enough to cover the upper and lower sections in one go, sections must be joined together so that the seams run chordwise, i.e. from the front to back of the wing, until a long enough blanket is made that can cover the spanwise length of the wing. This piece may then be wrapped around the wing structure with a final seam to close it along the trailing edge. In contrast to the first technique, therefore, there is only one seam running spanwise along the length of the wing, but there may be several or more chordwise.

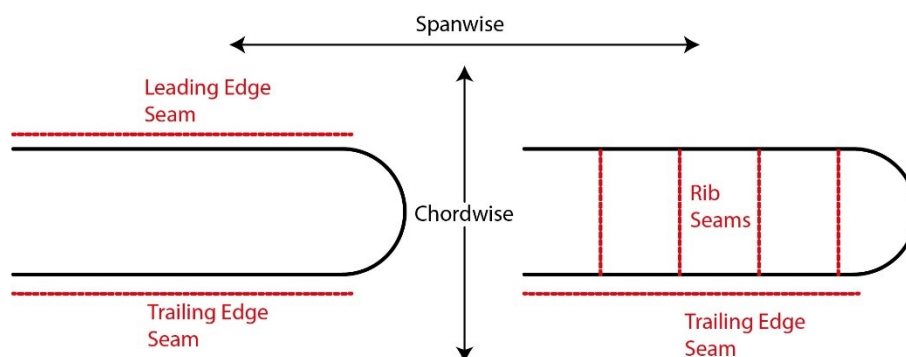


Figure 2-9: The potential location of seams on a doped-fabric aircraft wing depending upon how the wing covering is constructed

To finish securing the fabric in place, the fabric blanket is positioned over the frame and strips of fabric, known as reinforcing tape, are adhered with dope onto the blanket over each rib. The fabric is then sewn to the frame using lacing thread, with the stitch running the whole way around the rib, from the upper wing surface through the lower surface, and then back up again (Figure 2-10). Various knots and finishing techniques may be used to tie off each loop so that a failure in one part does not cause the whole length to unravel, and the whole seam is then covered with a final piece of fabric tape, the surface tape, to smooth and further reinforce the area. The surface tape is only applied after the whole fabric has already received one or two coats of dope to prevent it potentially becoming distorted due to different contraction rates with the stitched components beneath.

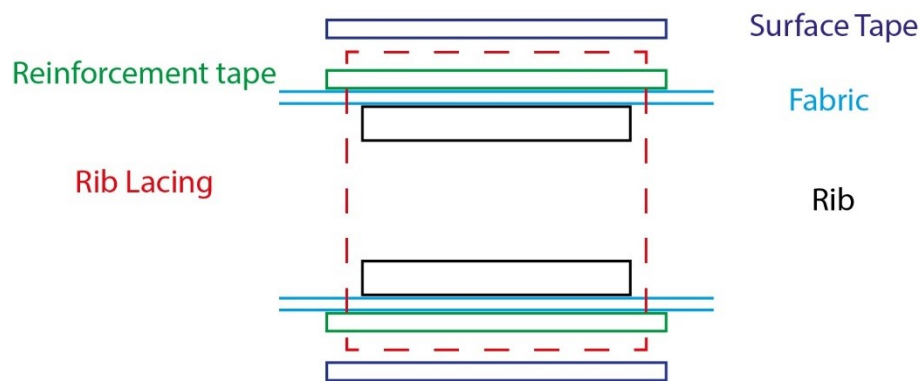


Figure 2-10: Cross section showing the layers used in attaching a doped-fabric skin over a rib member (adapted from (FAA, 1998 p.2-10)

Alternative attachment techniques include the use of screws or pins and such methods were used increasingly for later doped-fabric aircraft, such as Wellington Bombers and Hawker Hurricanes, which reduced the time-consuming process of sewing. In a Wellington Bomber, the interior frame was designed with multiple pin holes throughout the metal structure, so that the fabric could be quickly and easily pinned down.

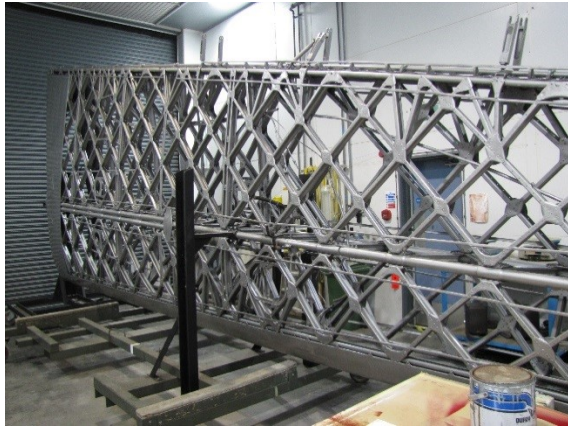


Figure 2-11: The internal structure of a Wellington Bomber whilst being reskinned at RAF Museum Cosford. Small holes used for pinning the fabric in place are visible in the structure

Once the fabric was secured down the process of doping could be started. Before the first coat of dope was applied, however, the fabric might be wetted with water to smooth the surface as water absorption causes the fabric fibres to swell and shorten, pulling out creases. On drying, however, this step has the drawback of resulting in a slacker fabric due to re-arrangement of the weave, an undesirable side effect of such a pre-dope treatment.

After wetting, the dope coating is applied, and each coat should be painted or sprayed normal to the previous coat and it is this process which imparts the final tautening to the material. The objective was to make the fabric surfaces drum tight and stiff, but could be overdone to the extent that the underlying truss structure could deform if excessive shrinkage of the doped-fabric occurred.

A final task to finish securing the seams and fabric was to apply finishing tape. For this a strip of fabric was doped over any potential weak points in the structure, such as seams and other attachment points. This strengthened these areas and created a smoother surface over any rough or inconsistent features. This step is only performed once several coats of dope have already been applied to ensure that the finishing tape is not distorted or rippled by the surrounding doped-fabric drying.

Any holes needing to be cut in the fabric for other features, such as cabling, inspection holes, and drainage, were inserted midway through the doping process once the fabric was already somewhat taut so that the hole would not distort with further doping and would be reinforced with finishing tape doped around their edges.

From the above description has identified that there are numerous potential weak points in a doped-fabric structure, namely seams and finishing points, but that these are heavily reinforced to reduce the risk of failure

and to ensure that the skin at these points is securely restrained. Between these securing points, however, such as between ribs, there is no further structural support or reinforcing of the doped-fabric.

It should also be noted that there are numerous steps involved in constructing a doped-fabric aircraft requiring skilled practitioners, from preparing the fabric, to securing it, finishing it and doping it. The ultimate quality of the aircraft therefore relies upon the skill of the workforce and the amount of time available at each stage, but that this factor is outside the power of the museum professional and is an inherent property of the object depending upon its history and previous treatment. Such issues relate to concepts such as authenticity and integrity, discussed further in section 4.2.

2.3.2. Dope Application

A final issue of concern when constructing a doped-fabric aircraft was the method of dope application. This was important because correct application of the dope had as much impact on the final doped-fabric performance as the formulation of the dope recipes or fabric selection. A major problem when doping an aircraft was 'blushing', when a white, cloudy precipitate formed on the surface disrupting the smooth continuous film. This occurred when doping in high RH conditions, such as outside during wet weather. Inoue proposed that blushing was caused by the precipitation of the cellulose ester in water onto the dope surface, explaining why it was a particular problem in high RH conditions. Blushing was further exacerbated if a high proportion of highly volatile solvents were present in the dope as these would rapidly evaporate, cooling the surface and causing more water to condense out of the atmosphere (Inoue, 1941a); Inoue 1941b).

Control of dope shop environments was therefore critical for a good result and manufacturers specified that shops should be kept at 65-70°F (c.18-21°C) to try and control RH levels (British Emailite Company Ltd., 1917; Cellon Ltd, 1917a, 1917b, 1917c; Royal Aircraft Factory, 1917a; Titanine, 1917a, 1917b). Very specific guidelines were also provided concerning the method to apply dope layers, stating that the first coat should be worked in with a brush to achieve good penetration and adhesion to the fibres, followed by unworked coats brushed on to create smooth, continuous films. Most specifications state that five or six coats should be applied. Later developments meant that by WWII spraying dope layers was a more practical technique than brushing, as it could create a more even finish much faster.

Concerns were also raised during WWI about the potential risks of mixing different types of dope together, and there appears to have been considerable confusion as to which dopes could be used together and the correct layering of structures. There were instances of dopes from different manufacturers being used together during

WWI which caused blistering and disruption of the dope coating (*Deputy Director of Equipment Communique to Airboard Office 29/10/1917 Ref 1901Q*, 1917). Strict instructions were therefore supplied as to which dopes could be safely used together before work could be done to assess which dopes were compatible.

The consequences of poor preparation and application of dope is clear from WWI field squadron reports when aircraft were delivered with dope films already peeling away from the wings, indicating that incorrect procedures had resulted in a very poor adhesion between the polymer film and fabric (*Major Commanding No 48 Squadron, 1918: R.A.F. Method of Doping Planes in B.F.2.b Machines. June 1918*, 1918). The confusion also led to the wrong types of dope being used as, despite directives stating that all front-line aircraft should be cellulose acetate doped by 1917 and marked accordingly, there are a range of communique indicating numerous mistakes occurred with many planes still receiving nitrate based dopes or being incorrectly labelled (*Brigadier General Director of Aircraft and Quarter Master General Letter to Air Board Office 21st October*, 1917).

It would seem likely therefore that manufacturers and suppliers were using whatever materials were available, and so statements of standardisation or best practice should be interpreted as statements of intent, rather than as truths as to what may or may not have been actually been happening on the ground.

2.3.3. Maintaining Doped-Fabric Surfaces for Flight

Almost inevitably some damage will occur to doped-fabric panels over time which must be repaired to maintain a flight-worthy surface. When a doped-fabric skins tears, one recommended repair is performed by sewing the two edges of the tear together and then adhering a piece of reinforcing tape over the area with fresh dope (FAA, 1998). In such repairs it is important to ensure that the final tape layer applied over the top is smooth and unwrinkled, and that it is fully saturated with dope before application, and then treated with several more coats of dope once in place. The addition of the patch is intended to further reinforce the area, preventing the tear from opening further, to create a smooth surface, and also to re-introduce a compressive force to re-tauten the surrounding material.

In the case of larger areas of damage or when a specific area of fabric has deteriorated to such an extent that it needs replacing, a larger repair is required. One approach is to cut out the entire panel of fabric affected between several ribs or other structural elements and install a new one in its place. This new panel will need to stretch across structural elements so that it can be sewn or pinned down using the same procedures as described for initially securing and doping the fabric. This process will take place above the original stitching and reinforcing tapes of the surrounding fabric panels already in place.

The most drastic form of repair that may be required is a complete recovering of an aircraft, but this is an expensive procedure both in terms of time and materials. Any recovering for flight purposes would need to comply with the standards and guidelines of the relevant aviation authority responsible for overseeing the works and such work also carries the same risks discussed in the section on the first covering of an aircraft, such as over-doping when the skin may shrink so much as to distort the internal framework and tear itself to pieces.

2.4. Summary

The foregoing discussion demonstrates that the physical properties of doped-fabric play a determining role in the types of aircraft and locations where it may be found. Doped-fabric was selected as it had the requisite stiffness to resist deformation from air pressure but was not sufficiently strong or stiff to act as a structural element. To this end, therefore, doped-fabric must be attached and supported by an internal framework.

The discussion also demonstrates that when considering doped-fabrics there is no single, standardised product. Doped-fabrics are the result of complex social, economic and technological factors, and the quality of the final doped-fabric could be highly variable depending on the quality of craftsmanship and raw materials available, as much as the selection of fabric type and dope formulation. Care is therefore required in making assumptions as to how far official standards, guides and procedures reflect the historical reality of practice, and it should not be assumed that historic aircraft would necessarily have appeared in a pristine condition even when fresh off the production line due to shortcuts in production methods.

There is, however, considerable uniformity as to the material types which one would expect to be present, namely a cellulosic fabric impregnated with some type of cellulose ester based dope. The uniformity of materials used in making dopes is demonstrated by the table of dope formulations found in the trade literature and archives (Table 2-3). Indeed, many are almost identical, varying only slightly in terms of ingredients or quantities used, with only a few exceptions, such as a formulation patented by Flatters based on casein. Beyond the specific recipe used, each doped-fabric may then potentially have unique properties and characteristics depending upon its own history, such as the drying environment and the level of care exercised in its application.

Finally, this chapter has hopefully drawn attention to the depth there is to this material. Although perhaps a somewhat overlooked aspect of aircraft history, the development of doped-fabric skins is a story of invention, experimentation and huge variety in what was for a considerable length of time a highly innovative and complex area of aircraft design.

3. Doped-Fabric and Conservation at the Science Museum

To understand the aims and outcomes of this research project it requires placing within the wider context of the work and objectives of the Science Museum. This is because as an institution, the museum has a limited amount of resources for the conservation of its collections which limit what can be realistically achieved. A description of how and where doped-fabric aircraft are displayed, will also provide insight into their conservation requirements and the opportunities and constraints set by the museum context.

This section will set out the conservation challenge at the museum with a review of the display setting of the doped-fabric aircraft and the environmental parameters in *Flight*, the Science Museum gallery where most of the collection of doped-fabric aircraft are displayed. It will also include a discussion of current conservation techniques employed at the museum and consider the wider structure of the museum's conservation department. It will, in addition, summarise the significance and condition of a selection of doped-fabric aircraft on display in *Flight*, discussing their history, value and previous interventions undertaken.

3.1. The Doped-Fabric Aircraft Collection at Science Museum, London

A review of the aircraft within the Science Museum collection is necessary to understand why these objects matter and how they have been treated both as working and museum objects. A summary of all doped-fabric containing aircraft identified in this study is given in Table 3-1 at the end of this section, p.71. but a more detailed discussion of a selection of aircraft will be given here to demonstrate the range of aircraft and the different types found in the museum. These aircraft are selected as they are considered particularly significant within the context of the museum's collection and they are the aircraft identified as of most concern by conservators at the Science Museum. Their technical file numbers are:

- Vickers Vimy (T/1919-476)
- JAP Harding Monoplane (T/1930-491)
- Hawker Hurricane (T/1954-660)
- Supermarine S6B (T/1932-532)



*Figure 3-1: A selection of the doped-fabric aircraft currently on display in *Flight*. From top left to right; the Vickers Vimy, the JAP Harding Monoplane, the Hawker Hurricane and the Supermarine S6B*

The main source of information regarding the history and display of these objects is the museum's technical files, managed by the museum documentation department. The technical files are a crucial resource for examining and understanding the history of objects within the collection as the files contain a range of documents and materials which might provide details about an object's acquisition, construction, use and correspondence with subject experts or sent in by the public.

The accumulation of information within technical files, however, is a somewhat arbitrary and ad-hoc process. The reliability with which documentation is added to the files depends somewhat upon the practice of different times, as well as the interests and efficiency of individuals involved ensuring items are filed properly. Many of the documents in the folders, moreover, appear to be chance findings sent to curators by acquaintances and other interested parties.

The information contained in the technical files, therefore, varies widely. Some aircraft, such as the Vickers Vimy, have technical files which run to many archival boxes of information built up over many years, whilst

others may only comprise a few sheets of paper, if that. The overview of an object constructed from a technical file review, therefore, is not necessarily complete, but does provide an understanding as to how and why the objects are of value, and how institutional perceptions and impressions of them have changed over time.

In some of the technical files samples of fabric from previous recovering projects and restoration works were found and details of these materials and samples removed for further study are provided in chapter 6.

3.1.1. The Vickers Vimy

The Vickers Vimy housed at the Science Museum is a very important object in the history of aviation since it is the first aircraft to have been flown across the Atlantic Ocean non-stop in June 1919. The aircraft was flown by two pilots, Alcock and Brown, taking 16 hours and 28 minutes to travel from Newfoundland, Canada, to Ireland. The Vickers Vimy used for the feat was originally intended as a bomber, the FB27 used during WWI, but was adapted during production to increase the fuel capacity necessary for the Atlantic crossing.

This is not the only Vickers Vimy in existence or on display. A Vickers Vimy bomber on display outside Adelaide Airport was the first aircraft to make the journey from Britain to Australia in under 30 days (Treccasi, 2001). This type of aircraft, therefore, appears to have been an important type in aviation development for increasing the range and speed of aircraft.

It is likely that the doped-fabric of the Science Museum Vickers Vimy was re-placed at least once before it was accessioned in 1919 after the flight across the Atlantic Ocean, as the aircraft was crashed into a peat bog on landing and suffered considerable damage (Bagley, 1981). Immediately after this restoration the Vickers Vimy was accessioned by the Science Museum though is not documented exactly how it was used by the museum, or where it was kept, but there are references to it being displayed by the museum in what was then known as the Western Gallery.

It was removed from the Western Gallery around 1960 for restoration work ahead of being displayed in *Flight*, and it seems likely that the doped-fabric was replaced as a part of this work as the technical file contains a sample of doped-fabric in an envelope entitled 'Fabric removed 1960-61 during renovation'. No details of where the fabric originated from on the aircraft, or whether any earlier recovering took place are recorded. The extent, materials and processes used for this restoration have not been recorded.

The aircraft has been put on display in *Flight* with large sections of the fabric removed from the fuselage so that the internal structure can be seen, and this was presumably done in the 1960's when the aircraft was recovered

for display. The doped-fabric surfaces are therefore not fully restrained along the fuselage edge, but are held to the frame by a chord passed through eyeholes along the length of the structure.

A second envelope entitled 'Vimy Fabric after treatment by Cellon 1962' contains three pieces of fabric. Cellon was a manufacturer of dopes based in south west London, and so it seems that they may have been commissioned, or that their dopes were used, to undertake some of the restoration work on the Vickers Vimy. The fabric contained in the envelope does not appear similar to other materials currently found on the Vickers Vimy or in the technical file, and it is not clear if the material was provided as samples, were removed from the Vimy or what work, if any, Cellon actually undertook.

The doped-fabric of the Vickers Vimy may have also undergone a variety of treatments and interventions since being installed in *Flight*. A letter dated October 14th 1975 from Moore, who seems to have been a consultant employed by the museum to advise on aircraft colours and dopes, mentions that he has found out about a plan by the museum to re-dope the Vickers Vimy all over using a cream coloured dope (Moore, 1975).

Moore questions the validity of this treatment arguing that the use of a clear, unpigmented dope would be more accurate, since this would have been used around the time of WWI to save weight. He also writes that the fabric and condition is still very close to the condition expected at the end of WWI when clear dope was used. The current colour and presentation of the Vickers Vimy is a cream, off white colour, suggesting Moore's advice in this instance was not followed and that the current colour of the aircraft was not how the Vickers Vimy appeared or was restored prior to the 1970's.

The current state and appearance of the Vickers Vimy, therefore, seemingly results from several different stages of intervention and restoration. The 'originality' and 'authenticity' of the fabric is clearly open to debate since it has been replaced on several occasions and then further reworked and altered. Quite radical treatment options could therefore be realistically considered, such as restoration and replacement of the fabric, though such a move would still need to be considered carefully due to the potential impact on the interior elements of the aircraft which may not have undergone as much alteration over the years.

3.1.2. JAP Monoplane

The history of the JAP Monoplane is somewhat obscure as it appears to have potentially originated in an act of industrial espionage. One account in the museum's technical file by a mechanic who worked on the aircraft, Freddie Snow, suggests that the design of the aircraft is based upon plans stolen from an aircraft being made for Bleriot, the first man to fly solo across the English Channel in 1909. According to Snow's account, the JAP

Harding monoplane aircraft crashed on its maiden flight and returned to the workshop, but never flew again (Snow, 1979).

This conflicts with a previous display label in the file, which states that the machine was first flown in 1910 and later in the year at the Blackpool Aviation Meeting, which an account in *Flight* ('Blackpool Flying Carnival', 1910) further corroborates. The origins of the confusion are not clear and it may be that two separate aircraft are becoming conflated between the accounts, but demonstrates the caution required in evaluating historic sources.

The technical file holds an envelope containing doped-fabric pieces which is dated as removed during a renovation in 1960-61. No details of this renovation are included, although it may have entailed extensive replacement of the previous doped-fabric skin. It was also during the 1960-61 restoration that a cross section of the starboard wing was removed to show the interior structure as a label in the file states how this was done on purpose to reveal the internal wing construction.

3.1.3. Supermarine S6B S1595

The Supermarine S6B is an important aircraft in the history of aeronautics and represented a significant technological development. It won a prestigious aviation race in 1931 called the Coupe d'Aviation Maritime Jacques Schneider, more commonly known as the Schneider Trophy. This was a major international race for seaplanes attracting entries from a range of countries, including Britain, France, Italy and Germany, with a prize of £1000 to the winning aircraft (though the race in 1931 was uncontested as no other entries were ready in time). Later that same year, on 29th September 1931, the S6B set an air speed record becoming the first aircraft to exceed 400mph.

The aircraft was technologically advanced for the period, using an all metal stressed skin wing construction and its floats for radiators, which required overcoming a number of technical challenges (Mitchell, 1931). The Supermarine S6B was developed by R.J.Mitchell, who went on to design the Supermarine Spitfire and it is thus part of an important technological narrative in aeronautics history. There are seemingly no other Supermarine S6B aircraft in existence as a second one commissioned at the same time appears to have been scrapped according to curatorial notes in the file. An example of a similar, slightly earlier model, a Supermarine S6A is on exhibition at the Solent Sky Museum in Southampton.

The condition of the Science Museum's Supermarine S6B has proven unsatisfactory to several visitors, who have written into the museum lamenting its poor condition and requesting it be restored to a pristine condition such

as, they argue, it would have originally looked (Ramsden, 2003, 2004; Manning, 2004). The paint layers are a feature of particular concern in these letters, the peeling paint of a dark blue upper layer with signs of a lighter blue undercoat interpreted as signs of neglect and a poorly done re-touching job. The authors advocates restoring the Supermarine S6B back to its original appearance, and the Supermarine S6A at Solent Sky museum is cited as an example of good practice as to how such machines are intended to appear.

This idea of restoring the S6B back to its 'original' appearance is an interesting observation, as the existence of the two paint layers is picked up in a piece of research by the museums curatorial team contained within the file (Bagley, 1984). Although hard to establish with certainty, accounts of the various painting jobs from the 1930's indicate that both the light and dark blue paint could be original to 1931, as the first paint applied was a bright blue type but was affected by oil from the engine and so was overpainted with a darker blue for the Schneider Trophy race. The curator notes there are even still signs of wear from the launch mechanism in the paint layers.

The originality of other aircraft features is supported by additional analytical work commissioned by the museum. Samples of sealing material thought to come from the fuel tanks were sent for analysis using Pyrolysis Gas Chromatography and Infra-Red Spectroscopy, and the report in the technical file suggests that these are made from natural rubber rather than synthetics (Loadman, 1989). This is not proof of originality per se, but it leaves open the potential scenario that these materials date to the 1930's construction as no evidence of later synthetic products not available at that period, which would conclusively prove such material is not original, was found. There is, therefore, no evidence that these aspects of the aircraft at least have been substantially interfered with.

The painted coats on metal surfaces have been analysed as part of a previous treatment project by a conservation student at the museum, Anne-Kathrin Klatz who undertook work to stabilise lifting paint flakes using 10% Mowilith 50 (polyvinyl acetate homopolymer) in toluene, but recommended that no further action, such as re-painting, be taken so as not to risk damage to potentially original paint layers (Klatz, 2002). Klatz also undertook Fourier Transform Infra-Red analysis on the paint and concluded it was cellulose nitrate based, and solubility tests suggested it would be damaged by use of acetone or xylene, but unaffected by white spirit or toluene (Klatz, 2003). A tear in the doped- fabric of the tail fin of the S6B was also conserved by Klatz who made this treatment the subject of a student report, which is unfortunately no longer available.

3.1.4. Hawker Hurricane

The Hawker Hurricane is an important aircraft in the Science Museum collection, as it is potentially the last known example of a Hurricane with doped-fabric wings, and the last surviving Hawker Hurricane from the Battle of Britain (Hamilton, 1982). Fabric skinned Hurricane wings are rare because, although originally designed with doped-fabric and at first common, they were gradually updated throughout the war with metal stressed skins (Mason, 1962, p.37).

The Hawker Hurricane used a novel approach to securing doped-fabric which avoided the need for stitching as the fabric was laid into recesses in the ribs and then held down using a U-shape flange bolted over the top, which was then covered with doped-fabric tape to smooth the surface (Allward, 1975). This design reduced production time and enabled the aircraft to achieve higher speeds without the fabric failing ('The Hawker Hurricane: The birth and growth of a great fighter described', 1940). It is therefore an important historical object both in technological terms representing the transition from doped-fabric to all metal skinned aircraft, and as a representation of an important historic event, the Battle of Britain.

There is a significant amount of information about the history of this Hawker Hurricane since its designation, L1592 KW-Z is known, enabling it to be traced through log books and other sources (*Internal Science Museum Memo on Hawker Hurricane L1592, Inv No. 1954-660*, 1985). It was made on 19th May 1938, and was used in combat before being shot down on 1st June 1940 when it caught fire. It was re-skinned and became a reserve aircraft in 615 squadron and a letter from one of the pilots to have flown it during this period was received which is a reminder of the personal, human stories these objects may also represent (Burrough, 2004).

After war service, the aircraft was assigned to 'museum purposes' and stored, though correspondence also claims it was displayed in Horse Guards Parade for a time under different markings, DT/A, and was then used in the 1952 film *Angels One-Five* when its markings were again changed to US/N (Davison, 2001).

The aircraft was bought by the Science Museum in 1954, when it was presumably already in separate pieces or subsequently disassembled for storage as a memo in the files claim it had to be re-assembled by Hawkers in 1961 before it could be displayed in the new *Flight* gallery. No further documentation of on-going repairs or maintenance are recorded, though it seems likely that the museum was continuing to apply dope. In Moore's letter contained within the Vickers Vimy file, he advises regarding the Hurricane, 'you should have some of the dope as it was specified for colours to supply to you' (Moore, 1975).

The above summaries of a few of the aircraft in the museum collection has demonstrated how important the collection is in representing the history of aviation and the value of such objects as heritage items. At the same time, however, it is difficult to construct an accurate pattern as to how such aircraft have been treated and managed using the archival records. Whilst many of the aircraft appear to have been restored when first accessioned by the museum and again in the 1960's, details about the extent of restoration works, the materials used and the process by which re-coverings were carried out are unfortunately extremely rare. Most work was largely undocumented, and where references do exist it is usually only as a few tantalising hints.

Some of the complexity in using seemingly everyday terms, such as 'authentic' and 'original', has hopefully also been demonstrated. Such terms may appear relatively straightforward on first consideration but convey highly loaded ideas and assumptions which may not be apparent on the surface so require careful use when applied to historic artefacts. The issue of such language, and how it has influenced conservation approaches, will be given more attention in Chapter 4.

Aircraft Name	Object Number	Location	History	Significance	Current Fabric Condition	Previous Interventions	Samples available
Antoinette Monoplane	1926-542	SM; Flight Gallery Hanging beyond visitor reach.	An Antoinette 1910 model it was designed and built in France, but owned and flown by H. Latham in England. It was donated to the Science Museum in 1926 by R. Blackburn.	An example of early aviation technology and associated with H Latham, an aviation pioneer and contender of Bleriot to fly across the channel in 1909.	Good. The wings and other fabric surfaces do not appear to be significantly deteriorated. A minor tear was noted in the fuselage and some minor failures in the fabric of the empennage section.	A note dated 4 th May 1926 from H Bentley notes the wing fabric is 'deteriorated greatly' but that they aim to renovate while retaining as much original material as possible. It is also proposed to leave part of the wing uncovered as is currently the case on gallery.	Fabric samples dated 1960-61 removed during renovation were also found.
Cierva C.24	1935-493	Loan Out L/2176/1.	Prototype built in 1931. Crashed Oct 1932 and probably not flown again. Donated to SM 1935. After 1960 restoration displayed at Mosquito Aircraft Museum	One off prototype of autogiro technology.	Not seen.	1960's repaired at Hatfield though fabric apparently not replaced. 2001 request to SM for repair work on flaking paint off metal and to replace fabric. Not clear if authorised.	
Cierva C30.A	1951-383	SM; Flight Gallery potentially in reach of visitors from raised walkway.	Unknown original build date. Impressed by RAF June 1940. Several accidents requiring repairs during service. Sold to SM May 1946(? Why is accession number 1951)	Off shoot of aircraft technology exploring autogiro technology.	Fair.	Overhauled by RAF apprentices at Halton in 1962.	
Cody Biplane No 304	1913-136	SM; Flight Gallery Hanging beyond visitor reach.	The SM plane was constructed for the Royal Flying Corp in 1913 based on the design of a biplane by Samuel Franklin Cody which won the GB army flight trials of 1912. After the first prototype failed in flight killing the pilot, the second plane was no longer used and donated to the Science Museum in 1913.	Only surviving plane constructed by S., Cody, an early aviation pioneer and arguably the first man to achieve powered flight in GB.	Good. No tears or previous repairs visible.	Original covering 'Pegamoid' (celluloid coated calico (?)) and recovered in 1913 when donated to museum. Recovered in 1976.	Samples from 1976 recovering.

Aircraft Name	Object Number	Location	History	Significance	Current Fabric Condition	Previous Interventions	Samples available
De Havilland 60 Moth	1931-27	SM; Flight Gallery Hanging beyond visitor reach.	Used by Amy Johnson for first solo female flight to Australia (20 days) in 1930.	Association with Amy Johnson and used for historic flight.	Good	Underwent numerous running repairs and alterations on flight to Australia, e.g. at Tjornal in India the wing fabric was ripped by bamboo and repaired (no details given). The tail surfaces were possibly replaced in India and the wings replaced in Australia. Bayley records the machine was 'cleaned up by de Havillands' before entering the museum.	
De Havilland DH84 Dragon Aircraft	1983-603 Pt1	Wroughton	Early British Airliner. 1933 delivered to Highland Airways Ltd. at Inverness. 1952-59 used by Air Navigation and Trading for sightseeing tours of Blackpool, 1962-1964 Beagle Aircraft Ltd used it for executive transport. Private ownership until 1971. Collected by Historic Aircraft Museum, Southend. 1983 given to SM, flown to Wroughton Airfield for delivery. 4439 total flight hours.	One of the oldest surviving British airliners in existence.	Unseen. From images appears fair.	Markings changed through various roles in operational life. Historic Aircraft Museum 'renovated' the fuselage, tail plane, starboard elevator, port mainplane and starboard mainplane fabric. Not clear what 'renovate' entails.	
De Havilland DH89 Dragon Rapide Aircraft	1981-2081 Pt11	Wroughton	Plane designed during early 1930's for passenger service, based on earlier Dragon design. SM collection one believed to be 1940 war production. Post war sold to Ceylon Air Academy. 1974 flown back to Biggin Hill to join Strathallan Collection. Interior stripped to allow extra fuel for this journey.	Early British airline.	Unseen. Reports of rats eating the floor in storage at Wroughton, (potentially eating the fabric too?)	1972 reported in good condition having undergone a rebuild prior to return flight. Running repairs throughout return and interior removed for fuel capacity.	

Aircraft Name	Object Number	Location	History	Significance	Current Fabric Condition	Previous Interventions	Samples available
Fokker E111 Monoplane	1918-210	SM; Flight Gallery. Hanging near raised walkway.	Captured German plane in 1916. Tested for comparison then offered to SM. Before SM display toured country and displayed in very poor conditions, e.g. under tent. Put on SM display 1923, fabric torn off by visitors. Put into storage and redisplayed 1963.	Technological example of early fighter technology. Related to specific event of pilot capture in WWI and rare chance for GB authorities to directly test German technology.	N/A. No fabric covering present.	Fabric tape on wings replaced in 1976. Original stored in Blythe House basement - unlocated. Date remaining fabric removed and location unknown.	
Hawker Hurricane	1954-660 Pt9	SM; Flight Gallery. Suspended from ceiling.	Built in 1938 and saw active combat in the Battle of Britain. Shot down in 1940 and caught fire so required extensive repairs. Used for reserve/training duties before transferring to 'museum duties' end WWII. Sold to SM 1953 and put on display 1961 in <i>Flight</i>.	Possibly the only fabric covered Hawker Hurricane left, some accounts claim it is the last HH Battle of Britain fighter in existence. As a metal frame covered with fabric it represents an important technological stage between earlier all wooden aircraft and later all metal types, and it incorporates a novel method for securing the doped fabric to the frame. Personal significance as tech file contains correspondence from a pilot who flew the plane and images of him stood in it with ground crew.	Fair. There are several tears on the upper wing surface whose cause is unclear. Possibly the result of damage from cleaning or climatic influence. These have been patched with the fabric and dope method, then repainted. There are also noticeable tears on the lower wing surface.	Possibly re-doped during the 1970's. Dopes used potentially coloured specially for the job.	
Hill "Pterodactyl" 1A	1951-218	SM; Flight Gallery Hanging beyond visitor reach.	Developed by Captain G. Hill in 1920's to try and reduce number of fatal training accidents by allowing for control even if stall speed passed.	Unique dead-end development in aeronautical history.	Fair. A tear is visible in the port wing but is not visually distracting.	Unknown.	

Aircraft Name	Object Number	Location	History	Significance	Current Fabric Condition	Previous Interventions	Samples available
J.A.P. Harding Monoplane	1930-491	SM; Flight Gallery Hanging beyond visitor reach.	Build for a man named Harding in 1910 by J.A. Prestwich and Co. Design closely based on Bleriot XI plane which made first channel crossing in 1909.	Evidence for early aircraft technology.	Poor. A single large tear runs the entire chordwise length of the starboard wing.	An image from 1932 shows considerable repairs conducted on wing to that point. The Science Museum stripped fabric from starboard wing to show the construction.	Sample from renovation in 1960-1961.
ME 163 - B1 type	1958-103	SM; Flight Gallery Hanging beyond visitor reach.	Early German prototype of rocket powered aircraft captured end WWII. Acquired by SM once military testing and analysis completed. All metal fuselage but control surfaces were fabric covered. Some modifications made for display - lighter nose cone fitted, and engine removed.	Aircraft represents major change in aeronautics technology with development of rocket power.	Good. No tears or previous repairs visible.	Reconditioned at RAF Halton in 1961. 1960's advice provided that clear dope should be applied to make paint layer glossier as otherwise too matte. Not clear if this was done, or if it was advised for aircraft before or after Halton works.	
Roe Triplane	1925-443	SM; Flight Gallery Hanging beyond visitor reach.	Early developmental prototype tri-plane designed by Alliott V. Roe and used by him for his first flights. Heated debate between several parties as to whether Roe was the first Englishman to achieve flight.	Very early example of early aeronautics technology and design	Good. No tears or previous repairs visible.	Originally covered in 'cotton-oiled paper backed with muslin'. Significant areas of the fabric were missing or damaged when arrived at the museum in 1925 so recovered 1927. Roe supplied paper that was 'ordinary linen backed packing paper and afterward varnished'. A dark-brown paint was also applied though no reason given. 1960's plane recovered to hang in aeronautical gallery. This finish varnished yellow due to	From 1961 waxed paper and possibly recovering material from 1927(?)

Aircraft Name	Object Number	Location	History	Significance	Current Fabric Condition	Previous Interventions	Samples available
						name of 'The Yellow Peril' given to the plane at the Blackpool Aeronautical Meeting.	
S.E.5a	1939-324	SM; Flight Gallery Hanging beyond visitor reach.	Plane originally designed as a fighter during WWI. Aircraft produced in 1918 and never used for combat, but adapted for skywriting by John Savage. Company using plane ran until 1932 in UK.	Development of sky writing technology - exhausts of special interest.	Good. No tears or previous repairs visible.	Confusing. Bagley assumes recovering occurred sometime between 1923-1939 as there is a silver dope layer topped by a brown-silver sky writing colour. 1960-61 recovering. Incorrect military marking and paint system used. Late 1980's Wings recovered at SkySport(?) and repainted in civilian design.	Fabric samples from 1960-61.
Supermarine Seaplane, S.6.B. S.1595	1932-532	SM; Flight Gallery. Displayed at ground level. Accessible to visitors.	One of two prototypes developed for Britain's entry at the 1931 Schneider Race (a prestigious air speed race between UK, France, Germany and Italy, though uncontested that year as only Britain's entry was prepared in time). Donated to SM shortly afterwards in 1932. Almost certainly on display from 1947 onwards, not clear how used before this time.	Represents a major aeronautical technology jump overcoming several technological problems of the time and incorporating all metal wings (fabric covered control surfaces). Winner of the Schneider Cup Race in 1931. Later in year broke air speed record. Design precursor of Spitfire fighter development.	Poor. The fabric on the rudder section has some large tears developing. Attempts to repair these have begun to fail.	Possibly overpainted. This seems unlikely and that the overpaint was applied at the time of the race. 2002 Flaking paint layers have been consolidated with Mowilith 50 in Toluene (10%). 2005 Flaking paints consolidated with Paraloid B-72 in Toluene.	Paint samples

Aircraft Name	Object Number	Location	History	Significance	Current Fabric Condition	Previous Interventions	Samples available
Vickers Vimy	1919-476 Pt1	SM, Flight Gallery. Lower wing edge and surfaces within easy reach of visitors.	Aircraft was assembled by Vickers Vimy company at Weybridge, probably using surplus components. Based on a bomber design but adapted for long distance flight, e.g. increased fuel capacity. After trans-Atlantic flight was donated to SM and displayed in Western galleries before moving to new Flight Gallery in 1963.	The first aircraft to make the trans-Atlantic crossing in 1918.	Poor. The lower wing surface in reach of visitors is highly damaged with numerous holes and tears. Patching with doped fabric has left the surface highly uneven. There are large tears in the fabric in the rear tail section.	Potentially recovered and repaired in 1918 after crash landing on arrival from trans-Atlantic flight. Possibly recovered again in 1961. 1970's it may have undergone re-doping with clear or cream pigmented dopes.	Bag of fabric samples with no context information recorded. Envelope containing 'Vimy fabric after treatment with Cellon 1961' Envelope containing fabric removed 1960-61 during renovation.
Wright Aeroplane Replica	1948-268	SM; Flight Gallery Hanging beyond visitor reach.	Replica of original Wright Flyer used to make first flight built at the Science Museum after the original was to be returned to the USA. Original plane recovered several times in 1920's. Used untreated white cotton.	No intrinsic historic value as not original. Technological interest as replica of first ever plane.	Fair. Some historic patches but no obvious contemporary damage.	Unknown.	

Table 3-1: Summary of Doped-Fabric aircraft within the Science Museum collection. SM – Science Museum site in South Kensington

3.2. The Condition of the Science Museum's Doped-Fabric Aircraft

The condition of the doped-fabric skins on the Science Museum aircraft varies widely. Some of the aircraft appear to be in an almost as new state, with no noticeable tears or marks on the fabric coverings. This is particularly true for those aircraft which are complete and suspended beyond touching distance of members of the public, and are thought to have been recovered during the 1960's and 1970's. Aircraft which appear in very good condition include the Se5a Fighter Plane, the Cody Bi-plane, the Roe Tri-plane, and 'Jason' the de Havilland Moth.

The most visible signs of deterioration occurring to the other doped-fabric aircraft are tearing of the wing coverings. The aircraft with doped-fabric in the most concerning condition is the Vickers Vimy as the underside of the starboard wing near the fuselage is the lowest point of the aircraft to the ground and has sustained frequent damage over the years (Figure 3-2). This is largely believed due to visitors poking holes when touching the aircraft, and there is one documented instance of a visitor seen punching a hole in the aircraft on purpose (Fordham, 2013).

A small, round hole in the Cierva C30a, and its proximity to the walkway, also suggests that the damage may have been caused by some sort of impact damage, possibly due to human action. The rounded shape and slight distance from the walkway suggest that it may not have been caused directly by hand, but by someone using something to poke the surface of the doped-fabric, such as an umbrella, though this is not documented and remains speculation.



Figure 3-2: Holes in the Vickers Vimy lower starboard wing (left) and Cierva C30a (right) potentially the result of human action

Of note also regarding the condition of the Vickers Vimy starboard wing is the number of doped-fabric patches that have been applied to the area nearest the ground. More details as to how these patches are applied will be

given in the following section but the large number suggest that many points of damage have occurred, and subsequently been repaired. Around these patches, moreover, some distortion of the wing surface is visible as undulations in the fabric (Figure 3-3). The condition of the trailing edge of the lower starboard wing is also very concerning, since along the entire edge where fabric patches have been used extensively the fabric has split open.

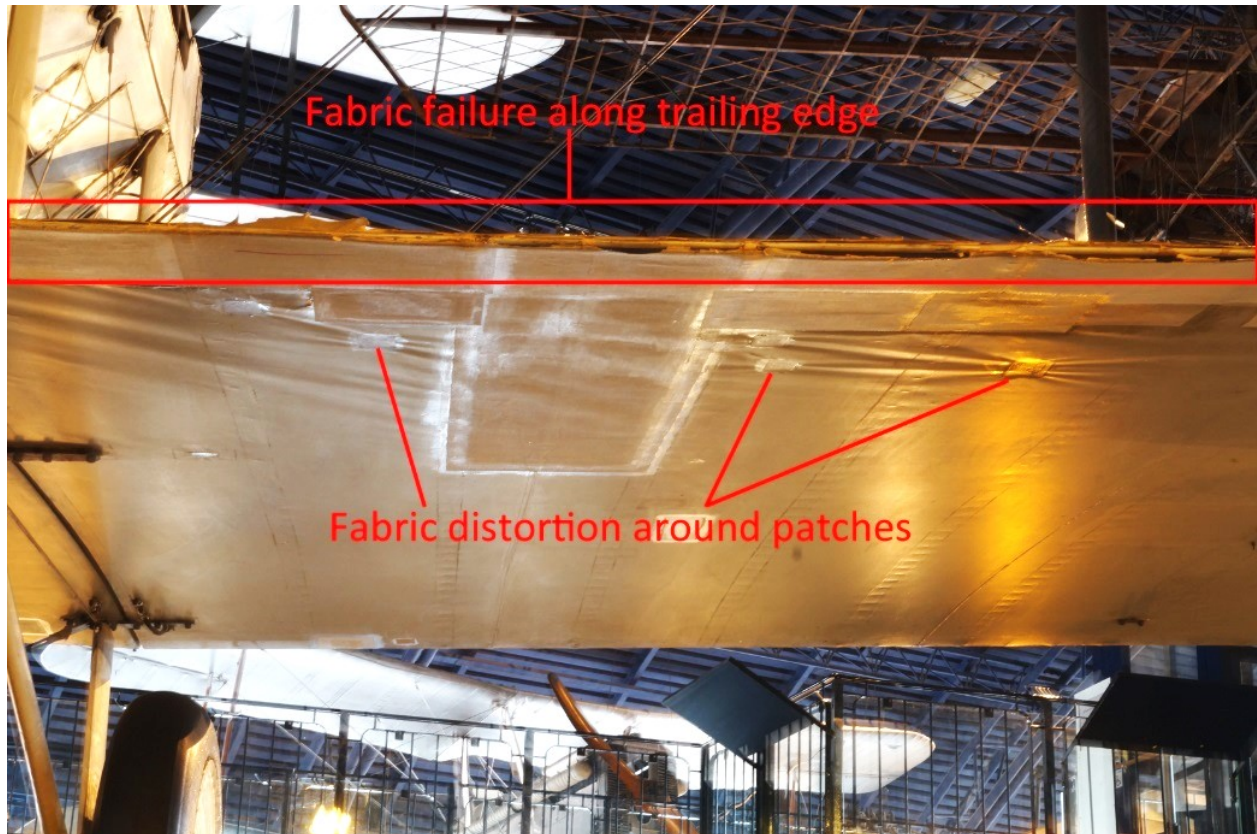


Figure 3-3: Tearing along the trailing edge of the Vickers Vimy lower starboard wing and distortion of the fabric around doped-fabric patches.

Besides those areas within reach of the public, there are tears occurring in regions well beyond human (or for that matter umbrella) reaching distance. The Vickers Vimy tail section has several tears running the full span of the structure on the port side whilst on the starboard side there are also several tears which appear to have begun opening around a doped-fabric patch repair, the date of which is unknown (Figure 2-4).

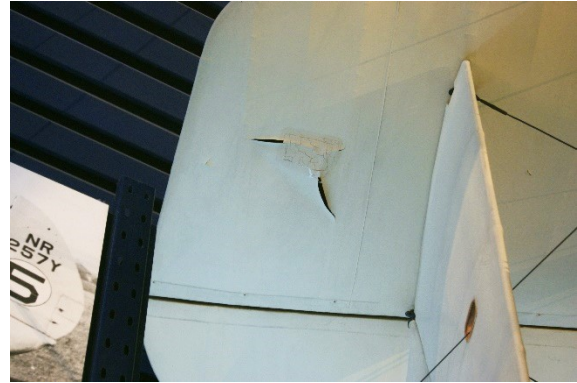
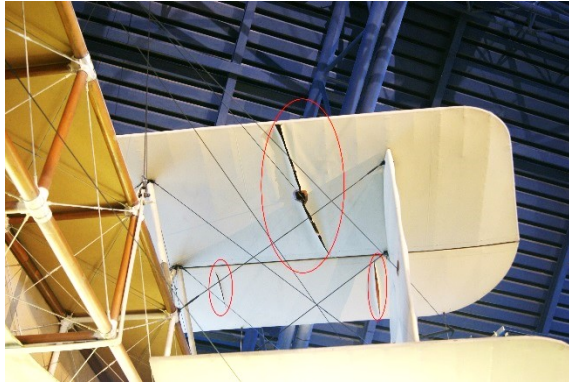


Figure 3-4: Tears in the Vickers Vimy empennage section beyond the reach of human action

These non-human induced tears, moreover, are visible in other doped-fabric surfaces, besides the Vickers Vimy. One tear in the JAP Harding Monoplane has opened the entire chordwise length of the starboard wing underside. Pictures from a 2008 cleaning project in the flight gallery indicate that there has been little change in the tear since the image below was taken in 2016. A similar, though less visible tear runs the full length of the Pterodactyl port wing, though there are no details as to how or when this occurred. Both of these aircraft are hung from the very top of the gallery ceiling, and so the tears seem highly unlikely to be the result of human interference.



Figure 3-5: Tears in the doped-fabric skins of the JAP Harding Monoplane (left) and the Pterodactyl (right) lying well beyond human interference

Tears are also visible in the side body of the Antoinette Monoplane, the rudder of the Supermarine S6B where a previous conservation intervention undertaken has failed, and the wing underside of the Hawker Hurricane. The locations of the Antoinette, Supermarine S6B and Hawker Hurricane indicate that these are also due to a failure mechanism not necessarily involving human interference.

3.2.1. Tear Opening in Action

Two new tears not believed to have been caused by human action were reported in the lower, underside of the wings of Vickers Vimy on 16/05/2017, one in the portside wing and the other in the starboard side. These new tears were reported by gallery attendant; there is no regular inspection or condition survey regime for aircraft, meaning that the exact dates when new tears open is often difficult to establish and the reporting of new tears depends upon the alertness and familiarity of gallery attendants to such damage.

Although potentially accessible from the ground, the location of the tears was towards the wing tips where the wings angle up from the ground sharply putting them beyond easy human reach and a ladder was required for access. Much less damage and patching is visible in these areas closer towards the wing tips than towards the fuselage.

The tears were first reported by gallery attendants who did not observe any visitor action which would have caused them and one end of both the tears was located near a defect in the wing, in both cases an eyelet where rigging passed through the skin, suggesting this was where the tear had first grown from.

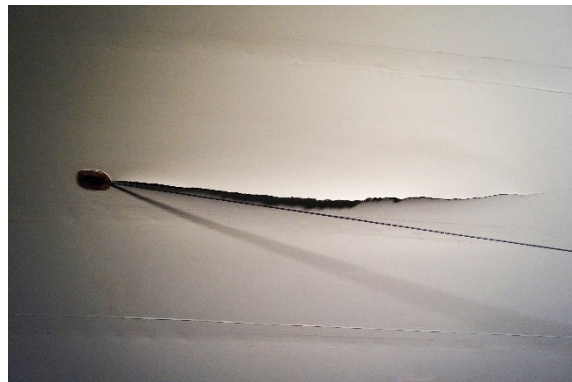


Figure 3-6: Tears observed in the starboard (top) and port (bottom) lower wings of the Vickers Vimy. The images on the right record the tear when first observed

Measurements of these tears were made, recording the growth over time (Figure 3-7). Although the date when each tear first opened is not known for certain, neither is believed to have been more than a week old when first observed based on gallery attendant reports, suggesting a very rapid initial growth rate. From that point on the tear in the starboard wing continued opening, though the rate dropped off markedly after two weeks. At some point, after 5 weeks, however, the rate of opening was seen to accelerate dramatically once again, until the tear grew the entire length of the wing to the trailing edge since when it has not grown further.

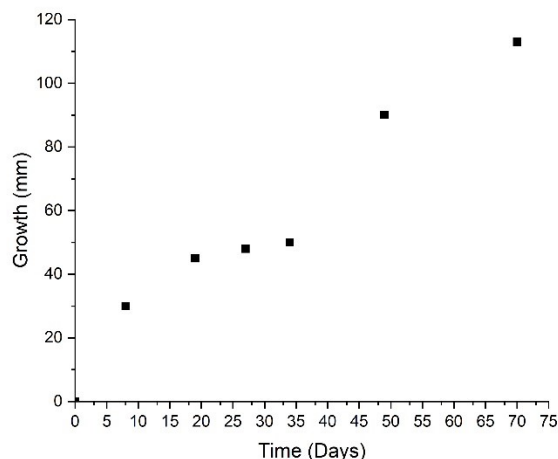


Figure 3-7: The growth of a tear in the underside of the lower starboard wing of the Vickers Vimy from 16/05/2017 when the tear was first reported to the conservation department

The second tear in the port wing, in contrast to the starboard wing, is much smaller and no further growth in the tear length was measured, which may be explained by the direction of growth of the tears. The starboard tear had opened towards the trailing edge, where there is a much greater length of fabric over which it can spread before reaching a limiting structural element, the trailing edge spar. The port tear, however, had opened towards the leading edge which was much closer to a spar, resulting in a faster stabilisation in growth.

The growth of the starboard tear demonstrates the issue conservators face at the museum. Once a tear opens, they are liable to continue opening, causing further damage and becoming increasingly noticeable to visitors. As

such a technique to stabilise and restrict growth is needed and a description of the technique used for this to date, and the resources available for such work, is provided next.

3.3. Conservation of Tears in Doped-Fabric Aircraft at the Science Museum

This section will describe the resources available to the Science Museum. This sets the context in which the doped-fabric aircraft are conserved and matters because this dictates what resources are available for their preservation and conservation at the Science Museum.

3.3.1. Conservation and Collections Care at the Science Museum

At the Science Museum, London, the conservation team comprises a conservation and collections care manager, a senior collections care conservator, an engineering conservator, an objects conservator and four conservation assistants. This comprises a total of 8 core staff members. Staffing at the museum's storage sites also tend to be small, with a team of approximately 4 core conservation staff again based at the London store, Blythe House, and the museum's large object facility, Wroughton, respectively.

Alongside core staff, project conservators are often employed on temporary contracts. The numbers of project conservators at different sites can fluctuate significantly over short time scales depending upon the specific project demands and funding available. The department may also host students and interns from a few weeks to almost a whole year, which demands considerable resources to manage.

Space constraints at sites are also worth considering. The Science Museum has a modest sized laboratory where objects can be conserved, as well as several limited spaces for short-term storage of objects. These spaces are often filled due to demands for working space from new galleries and exhibitions. The size of objects which can be treated in such spaces are also limited by the access routes, and there is no possibility of moving a doped-fabric aircraft, even once disassembled, off display to treat it elsewhere on the Science Museum's South Kensington site.

The only site available to the museum with sufficient space for undertaking large-scale interventive work on an object as large as an aircraft is the large object storage site based at Wroughton. Even at Wroughton, however, the actual space suitable for conducting treatments is limited. Demands from other projects, such as gallery installations, mean that such space is in constant use, so only high priority objects may be fitted into these areas.

The staff and space resources available to the Science Museum conservation team are therefore very limited. Prioritisation of projects within the museum which have strict deadlines, such as the installation of galleries and preparation of objects for loans, tend to dominate conservation work schedules.

Finding sufficient staff resources to properly document, monitor and carry out on-going repairs to the doped-fabric aircraft at the Science Museum, therefore, is a challenge. This is largely because the objects are, in the grander scheme of things, not a high priority as *Flight*, where most doped-fabric aircraft are displayed, is somewhat aged now having been installed in the 1970's.

Compare these resources for managing aircraft at the Science Museum to the author's impressions from a trip to visit the conservation department at the RAF Museum Cosford ¹. Although uncertain of the exact staffing levels, the author met two technicians specifically working on treating doped-fabric aircraft, with a purpose built doping studio. This is a specially designed space, fitted with the appropriate extraction and heating systems necessary for large doping projects. Beyond this the author met about 5 or 6 more technicians working on other aircraft in a further hangar, and this was not the entire staff he observed operating within these spaces.

This brief, anecdotal comparison in space and human resources suggests the Science Museum conservation department is far less well-resourced than Cosford. A direct comparison of the two institutions in such a way would be a mistake, however, since the context, skill sets and staffing requirements of the two organisations is totally different. The Science Museum is certainly not as well equipped to deal with aircraft and large-scale doping projects as Cosford, but then these are not regular projects as at RAF Cosford.

It is against this context which the aims and outcomes of this project needs to be understood and conducted. Developing conservation outcomes for doped-fabric which require large investments of time and finances would be of very limited value to the Science Museum given its current state. Of course, this context may change, and a potential re-development of the aviation collections could occur enabling greater investment, but it is likely that such resources would remain limited and only available for a short time.

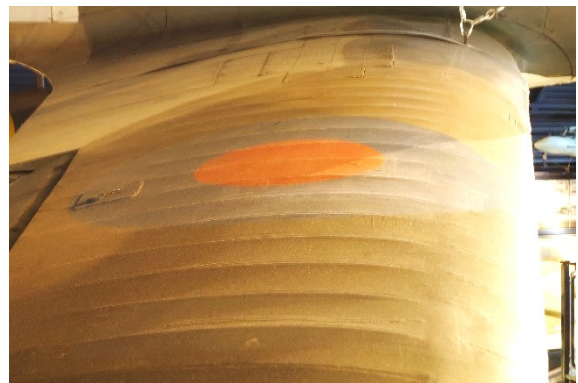
3.3.2. The conservation of Doped-Fabric Aircraft

The preferred method at present for conservation of doped-fabric skins at the Science Museum is using a doped-patch to cover the tear area, as this is believed to be the most structurally sound method of preventing further tear growth and re-imparting tension to the wing which may have sagged when the tear occurred. The

¹ Site visit by author to RAF Museum Cosford, on 16/04/2015

following account of how aircraft doped-fabric patches are applied is based on first-hand experience working with the Engineering Conservator, Richard Horton (ACR), treating a tear on the Hawker Hurricane in 2013 during a student placement at the Science Museum (Figure 3-8).

Patching is carried out using aircraft 9F1 Irish-linen and Randolph 9701 Clear Tautening Butyrate Dope (a list of suppliers used throughout this thesis may be found in appendix A). A rectangular area of the linen fabric is cut to size so that it covers the entire area of the tear, extending over the tear ends and to either side. The size of the area surrounding the tear which the patch covers is judged by eye and experience as to what is necessary for a strong bond. The patch is cut using pinking scissors, which create a jagged edge pattern, and the corners of the patch are rounded. The patch is then brushed with a 50% (v/v) solution of the dope diluted in acetone to give it an initial impregnation away from the aircraft.



*Figure 3-8: The process of applying a dope-fabric patch to a tear in the Hawker Hurricane on display in *Flight*. Top left to right; a tear in the Hawker Hurricane; working at height to fit a linen patch to the tear area; applying dope to secure the patch in place; the tear seen from the walkway after in painting (images ©Richard Horton/The Board of Trustees of the Science Museum, London)*

The surface of the aircraft is prepared by first sanding the area over which the patch is to be applied to roughen the surface. This is then wiped with distilled water to remove any residues and create a clean surface. Once the size of the patch is satisfactory it is secured in place on the aircraft by application of a first coat of dope. This first coat is again a 50% solution in acetone, as was used to impregnate the patch, and is brushed on until the patch appears saturated. The edges of the patch are smoothed down constantly to ensure a smooth, strong adhesion to the substrate.

The first coat is allowed approximately one hour to dry before a second dope coat again diluted 50% in acetone is applied in the same manner as the first, after which work on the patch must usually be suspended due to the opening hours of the museum. It may therefore be at least 24 hours, if not several days or weeks depending on the conservator work-loads before the final stages of work are completed.

After the first two diluted coats of dope are applied, any following coats of dope are applied undiluted, so the dope is used as received in the tin. The number of coats may vary between about 2 to 4, depending upon the feel and finish of the patch after each one. These coats of dope are brushed on until the patch appears saturated, with care being taken to ensure the edges are well adhered. To ensure the edges of the patch are strongly adhered, the dope is applied slightly over the edges of the patch to the surrounding aircraft fabric. The patch may then be finished off by in-painting so that the colour of the patch blends in with the surrounding fabric. Acrylics have been used for this at the Science Museum.

A successful patch is considered one that has a strong adhesion to the aircraft substrate, feels taut and smooth when touched, and is not immediately noticeable on casual inspection. Flicking with the finger should produce a slight ringing sound, indicating that the patch has adhered properly and shrunk, re-introducing tension to the wing and surrounding area. This patching method is very similar to the techniques discussed in the section 2.3 regarding maintenance techniques for keeping doped-fabric aircraft flightworthy. The main difference is that the technique used at the Science Museum does not involve sewing of the tear edges together first, though on some of the patches visible around the gallery seam lines are visible, suggesting this was done previously.

The main advantage of this patching method is the ease and practicality with which it can be carried out. The technique is simple and straightforward, enabling it to be applied in the gallery working environment, which can be challenging. Work often needs to be carried out at height or on the underside of a wing, at which point the conservator may need to be working at arms' length, upside down on a ladder or other high platform. A simple technique, therefore, which can be applied when manual dexterity may be limited is crucial. Other limiting

factors, such as lighting, time constraints due to opening hours and other work demands are also in favour of this technique, which is relatively quick and easy to accomplish.

As already noted, on certain aircraft there are numerous patches already, suggesting that this technique has been widely applied for some considerable time. These patches are almost certainly not from the working life of the aircraft, since as is discussed most were re-covered for display in the 1960's and 1970's.

3.3.3. Research into Tear Repair at the Science Museum

There are concerns within the conservation department at the museum, however, that the process of doped-fabric patching may be causing further damage to the doped-fabric substrates in the long-term due to the shrinkage of the doped patch re-introducing forces into the wings which lead to new tears elsewhere and, as has already been noted, the effect of the shrinking patches may be manifesting themselves visibly in the deformation of the lower surface of the Vickers Vimy starboard wing as seen in Figure 3-3.

The Science Museum has on several occasions considered alternative tear repair techniques for the wings. A memo found in the conservation department's files dated 11th February 1986 from Fieux Restoration Laboratory Inc. to Anne Moncrieff, a former conservator at the Science Museum, discusses the possibility of adopting a technique used in paintings conservation known as lining to conserve the doped-fabric on the tail of the Supermarine S6B (Fieux, 1986). Lining is a process in which a supporting backing is adhered to the back of a textile or canvas. The idea of this process is that the support should be stiffer, and hence prevent movement, and thus failure, of the supported material. This process will be discussed in further detail in chapter 5.1. There is no evidence that this idea was taken further, however, or that any further serious research into it was conducted by the museum.

Several students undertaking internships at the museum have also undertaken research into the failure of doped-fabric aircraft. Beesley (Beesley, 2009), as part of a master's research project, sought to develop new approaches by which patches might be applied to the reverse, interior side of the aircraft skin, and investigated standard materials used in conservation which might be suited for this. She developed a technique in which a metal plate could be inserted behind a tear and secured into position by sewing it into place. This metal plate could then provide a surface to apply pressure against patches when adhering them in place.

Beesley used this pressure to test the effectiveness of heat-set adhesives common in conservation practice for fixing patches in position, such as Beva 361, Lascaux 360 and Lascaux 498, although only their initial performance was reviewed, and no long-term or aging studies were undertaken. This technique although ingenious, has not been used by the museum conservators since it is a tricky technique to perform in well-lit

laboratory conditions, and even more difficult atop a scaffold tower. The issue of removing the metal plate is also one which is difficult to achieve without access through surrounding tears.

Beesley also analysed the covering of the Vickers Vimy using FTIR-ATR and identified the dope as cellulose acetate though attempts to investigate the material using Raman spectroscopy failed due to fluorescence of the material.

This amounts to the state of the Science Museum's knowledge regarding the aircraft and the issues as to their conservation. As such there are many suspected problems, yet limits on time and resources prevent investigation and development of a preferred solution. As such, this project was required to better inform approaches.

3.4. The Flight Gallery

A significant proportion of the Science Museum's collection of doped-fabric aircraft are housed within the Museum site in South Kensington, displayed in *Flight*. This gallery, opened in the 1970's, explores the history and development of aviation. The structure of the gallery is based around a linear, historical progression, with the earliest aircraft at one end of the gallery and later designs on display as one moves through the space. Aircraft selected for display range from early gliders built before powered aircraft, through to doped-fabric designs, then modern commercial and military jets.

Flight is located on the 3rd floor at the top of the museum, and is designed to replicate the inside of an aircraft hangar. It is a large, open, rectangular space with the long axis running east to west. The entrances are open archways located at the East and West ends, so that visitors pass through the gallery along its length. There are windows running along the whole length of the North face of the gallery by which a series of engines have been placed on open display. Further, un-covered windows are located high up at the East and West ends of the gallery. The windows have had UV filters applied though direct sunlight still enters the space.

The doped-fabric aircraft are all on open display and nearly all are suspended from the ceiling. This makes *Flight* a very crowded display area with aircraft being hung over and around each other or above showcases. There is also a raised walkway running through the centre of the gallery to enable closer inspection of the aircraft. The density of objects and location on the 3rd floor has consequences for access, limiting the working space in which scaffolding or other platforms can be used and making it extremely difficult, if not impossible, to remove an individual aircraft from display.



Figure 3-9: Views of *Flight*. Left, the view from the JAP Monoplane looking westwards and right (image ©The Board of Trustees of the Science Museum, London) a view from the raised walkway looking eastwards.

Further doped-fabric aircraft are exhibited in other locations of the museum. At the centre of *Mathematics: The Winton Gallery*, is a doped-fabric aircraft, the Gugnuc, and a doped-fabric aircraft is also displayed in the *Making the Modern World*. In these instances, the aircrafts are parts of larger, eclectic ensembles of objects and represent the development of aviation in relation to other technological and scientific developments rather than as a field of study in its own right.

Aircraft not on display at South Kensington are stored in aircraft hangars at the Science Museum Groups large storage site in Wroughton, Swindon. This site is a former World War II airfield and post-war RAF base, and the museum uses the hangars left from the site's time as a military base. There has been a review of the environmental storage conditions at the site recently due to plans for building a new storage facility at Wroughton (Leskard, 2015). The condition of the Wroughton hangars varies widely, depending upon their age and the resources invested into their upkeep and management. Certain areas of the site do have some form of climate control, but these are limited and unable to accommodate one object the size of an aircraft, and certainly not a whole collection of them.

This project will focus upon the aircraft currently displayed in *Flight* at the Science Museum in South Kensington. These are the aircraft which the Science Museum conservation department is most concerned about given that this is where key objects from the collection have been selected to go on display and where deterioration to the doped-fabric skins is considered to require most immediate attention given its public visibility. It is also the area of the museum where the problem of access and treatment options is most challenging.

3.5. Flight Gallery Environmental Monitoring

The Science Museum monitors its internal exhibition spaces using a system of Hanwell M4000 radio data loggers. These measure temperature and Relative Humidity (RH) at regular intervals, which are recorded using Hanwell environmental logging software. One such data logger has been recording information at 15 minute intervals in *Flight* since 2012. The logger is positioned at about head height against an internal wall at the east end of the gallery.

Due to an unidentified technical fault of the M4000 logger there are large periods where data is not recorded. Only data for the years 2015, 2016 and 2017 has been used as these are the most reliable long-term periods for which data is available, with only two short spells, 22-31 May 2016 and 4-31 December 2017, where data was not available.

Temperature and RH are generally considered to be two of the most important environmental factors which can affect the stability and long-term preservation of objects within museum environments. Studies have linked object degradation with environmental parameters, although the mechanism through which this occurs varies and will be discussed in further detail in chapter 5.

RH is given as a percentage, representing the probability of moisture condensing out of the atmosphere. It is calculated using equation 3.1:

$$\text{Relative Humidity} = \frac{\text{Actual vapour density}}{\text{Saturation vapour density}} \times 100 \quad [3.1]$$

The saturation vapour density, defined as the point at which there is sufficient water in a given volume of air that moisture will condense onto a surface, is temperature dependent. A rise in temperature increases the saturation vapour density as the increased the kinetic energy of water molecules makes condensation less likely, leading to a decrease in RH. A decrease in temperature, conversely, lowers the saturation vapour density, leading to a rise in RH.

Light monitoring at the Science Museum is not widespread or regular. Spot checks of the lighting levels in new cases is conducted but on-going monitoring of levels in galleries has not been carried out, and so there is no long-term data with which to judge the conditions in *Flight*.

3.5.1. Relative Humidity (RH) and Temperature

Plots showing RH and temperature against time for the years 2015, 2016 and 2017 are provided in Figure 3-10. Box whisker plots of monthly temperature and RH have also been created (Figure 3-11 and Figure 3-12). The statistical values for calculating the box plots are provided in Appendix B.

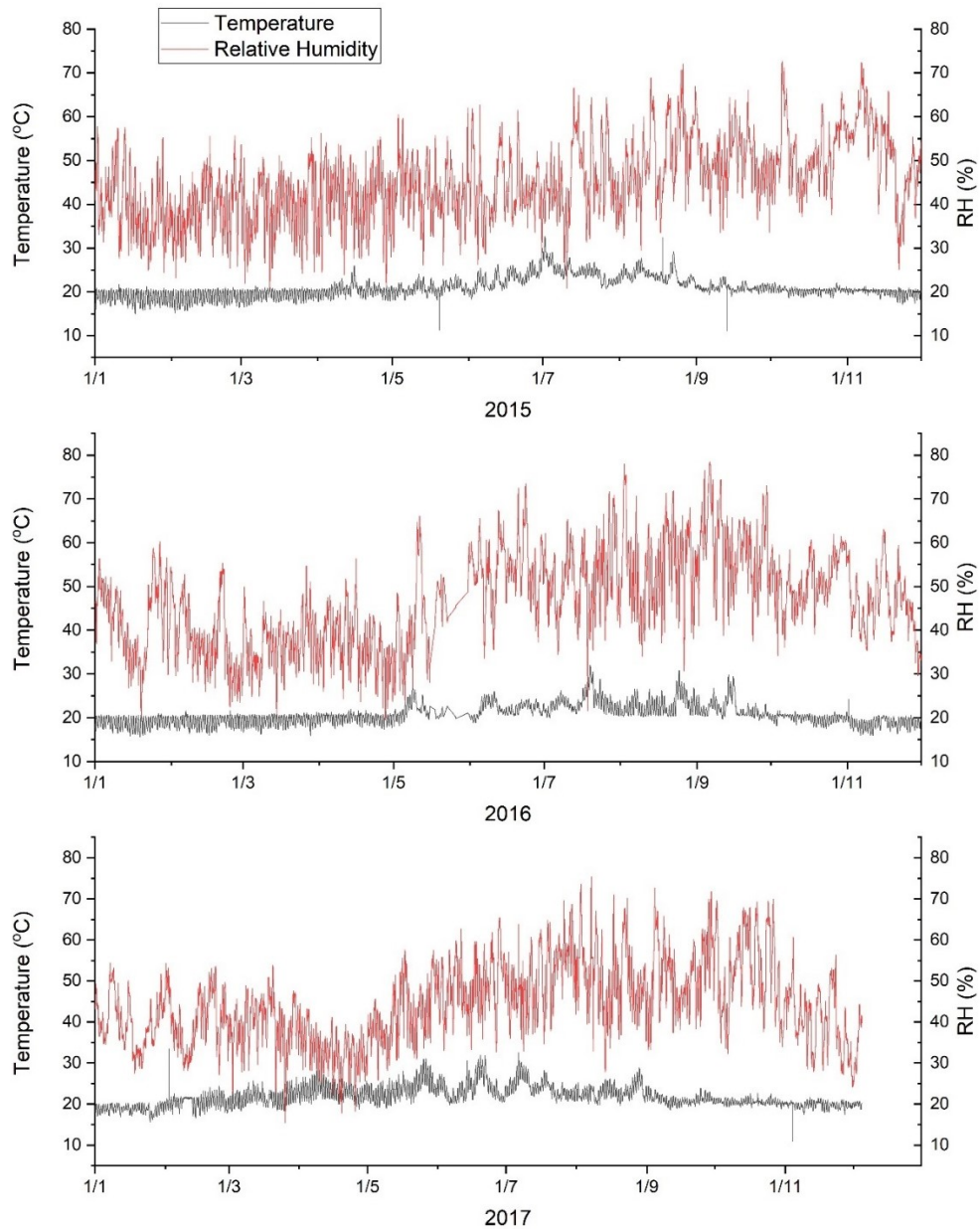


Figure 3-10: Plots of temperature and relative humidity against time in *Flight* at the Science Museum in 2015, 2016 and 2017

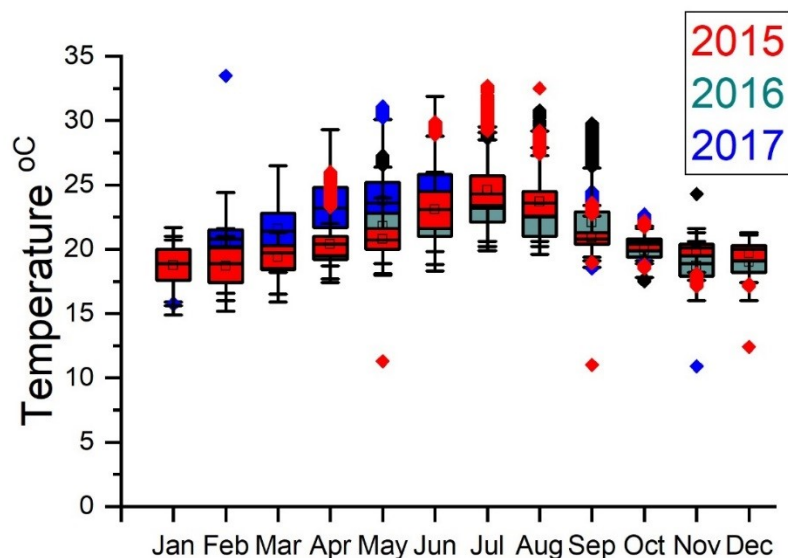


Figure 3-11: Box whisker plot showing monthly temperature changes in 2015, 2016 and 2017. The median is represented by the solid line at the centre of each box and the size of the box the range from the 1st to 3rd quartile, which represents 25-75% of the data points. Error bars show the range within 1.5IQR and outliers are depicted by $\diamond$. The mean average is shown by $\square$.

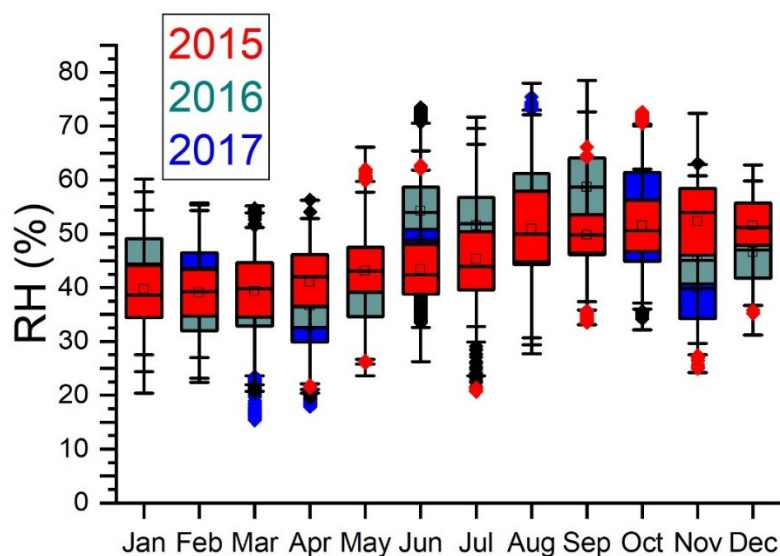


Figure 3-12: Box whisker plot showing monthly relative humidity changes in 2015, 2016 and 2017. The median is represented by the solid line at the centre of each box and the size of the box the range from the 1st to 3rd quartile, which represents 25-75% of the data points. Error bars show the range within 1.5IQR and outliers are depicted by $\diamond$. The mean average is shown by $\square$.

There are noticeable patterns in the temperature data obtained from *Flight*. During the autumn, winter and early spring months, roughly September/October to April/May, there is a repeatable pattern over a 24-hour cycle (Figure 3-13). The maximum temperature during afternoon, daylight hours is very consistent, approximately 21-22 °C, which then drops overnight to a less consistent level between approximately 15-18°C before rising back to a high point during the day.

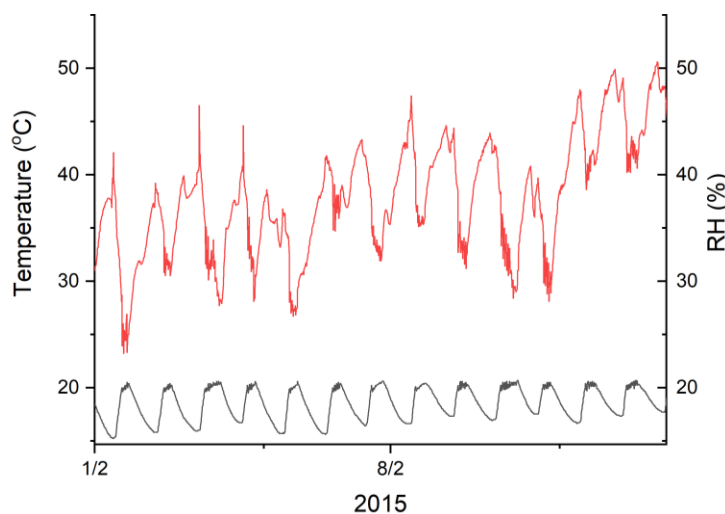


Figure 3-13: Temperature and RH in *Flight* during the first two weeks of February 2015

The regularity of the temperature pattern over 24-hour cycles is attributable to the museum heating systems. The consistency of the temperature control at the Science Museum can also be seen in Figure 3-11 of average monthly temperatures. During winter months the average temperatures are relatively consistent and little spread in the data is observed.

The short-term 24-hour cycling of temperature during winter is reflected in the RH data, with a peak in temperature tending to correspond to a trough in RH, and vice versa over short-term periods. This process reflects the relationship of RH on temperature as discussed in Equation 3.1. From Figure 3-12 it seems average RH is centred around approximately 40% and largely fluctuates somewhere between 30-50%, though it may also fluctuate between considerably between wider bounds of about 20-60%. Large changes can also occur over short time frames, which are presumably exacerbated by the fluctuating temperature due to the museum heating.

The RH cycle is not as steady or consistent as that observed for temperature, however, and there are periods when it does not appear to be temperature dependent as expected, rising with an increase in temperature and vice versa. The fact that RH broadly corresponds to the temperature pattern, but does not follow it closely indicates that the space is not well sealed, and the actual vapour density of the space is being strongly influenced by external weather conditions.

During the late spring, summer and early autumn, approximately April/May through to September/October, the day to day temperature is much less consistent and begins to rise on average compared to winter/autumn temperatures. This is presumably because the heating system is shut off and the temperature becomes dependent upon external temperatures.

From Figure 3-11 it can be seen that this increase in average temperature seems to peak roughly around July, before dropping away again towards autumn. The average summer temperatures also have a much greater spread than the winter temperatures, indicating that less control is being maintained of the temperature during this period, and so the values are likely a closer reflection of the outside weather conditions.

There are also changes in RH when moving from winter to summer with an increase in average RH during the summer months compared to winter, though this pattern is not as consistent as that observed for temperature. This rise in RH is presumably due to the removal of winter heating, which caused artificially low RH levels by heating the air entering the space from outside during the winter months. The average RH during summer appears to be somewhere around 50%, and may reach very high levels, above 70% though only for relatively short periods.

This review of the environmental conditions on *Flight* show that it is highly variable with very few controls. Where controls are in place, they appear to be for visitor comfort rather than to control display conditions, as evidenced by the constant cycling of temperature during the winter months. During summer no environmental controls appear to be in place, and the conditions are probably highly dependent on external weather conditions. The evidence shows that the aircraft are consequently subjected to regular changes in RH and temperature over both relatively short time periods, from 24-hour cycles, to longer-term cycles due to climatic, seasonal changes.

3.6. Summary

The above review has shown that the Science Museum exhibits important and valuable doped-fabric aircraft from the history of aviation in *Flight*. The significance of aircraft vary, with some representing important technological developments and others a connection with important figures or events in aviation, or a combination of both.

Many of the aircraft have had extensive maintenance or restoration work conducted upon them in the past, whether as working, flying machines or static, museum objects. The exact nature and scope of such work, however, is rarely recorded. It appears likely that most aircraft underwent either a partial or entire replacement of the doped-fabric on entry into the museum, and then again during a large re-development of the museum's flight display during the 1960's and 1970's.

Despite this recovering, many of the aircraft skins are now showing signs of damage, most notably tears in the doped-fabric skin. The cause of these tears in certain cases is likely human, particularly in the lower section of the Vickers Vimy wings, large parts of which are easily within reach of visitors. Other tears, however, are well beyond the reach of visitors and the failure mechanism in these areas is unknown for certain.

When tears occur the Science Museum uses a technique of doped-fabric patching to attempt to control the damage. These patches, although thought to be very effective at preventing further tear growth and easy to apply, are believed to potentially cause further damage to the aircraft due to the compressive force of the patches pulling on surrounding historic material. The most obvious area where this has likely occurred is around the trailing edge of the Vickers Vimy lower starboard wing where the fabric has pulled apart and distortion to the fabric is clearly visible around some patches.

4. The Museum Context of Conserving Doped-Fabric Aircraft

The conservation profession has its own sets of ethics, concepts and codes of practice. A discussion of these concepts and principles is necessary since they direct how conservators work and inform their decision-making practice. Application of these principles explain why certain factors may be considered important within a museum context when determining treatment decisions, whilst others may not be given as much attention.

Organisations and groups have attempted to codify conservation ethics, and thus create a standard against which conservation practice may be judged. The publication of Conservation Charters, for example, represent attempts to define how conservation should be conducted to be ethical (ICOMOS, 1964; Icomos, 1994; Australian ICOMOS Inc., 1999).

The development of professional conservation bodies at national and international levels has done much the same thing, as these bodies publish their own sets of standards which their members are expected to adhere to (UKIC, no date; American Institute for Conservation, 2015; ICOM, 2017). Within the UK the Institute of Conservation (ICON) has also introduced a process of accreditation, whereby conservation professionals can gain a recognised status which acknowledges they adhere to these standards. The following sections will explore these standards and ethics in more detail.

4.1. Values and Significance in Conservation

This section will discuss two crucial issues in conservation management, the ideas of value and significance.

These two ideas are central to any discussion of heritage conservation since they permeate throughout many of the principles and ethics conservators choose to apply, and are thus at the root of many concepts and principles currently used in conservation. Value and significance in heritage involve understanding what feature or quality of an object makes it worth preserving in some way, but there are various ways in which these ideas may be approached and understood.

4.1.1. Tangible and Intangible Qualities

An important starting point in the discussion of value and significance is the theory of two types of value; tangible and intangible (Odegard, 1995; Clavir, 1996). Tangible value relates to the physical form of a thing, its material being and our ability to interact with that through physical interaction, whether sight, touch, smell etc. This tangible value could be expressed in all sorts of features, such as the weight and shininess of a metal object or the smoothness of porcelain.

Conservation and heritage management have in general tended to place a great deal of emphasis on the tangible value of objects, wishing to retain the original materials, shape and appearance in which an object was made. In focusing on the physical form of an object, change, or the risk of change to a physical characteristic become undesirable and a threat to an object's value. There is therefore an emphasis placed on maintaining objects in stasis, preserved in a physically unchanged form for the future.

Conservation has, however, increasingly become aware of the limitations to our understanding of heritage when considered purely in terms of tangible aspects, and has increasingly explored the issue of intangible value (Giaccardi, 2011). The intangible value relates to those aspects of an object which go beyond its physical properties and could relate to a whole range of social, cultural, spiritual and religious ideas.

A good case study of such processes comes in the form of modern art sculptures made of chocolate (Skowranek, 2007; Wharton, Blank and Dean, 2011). In such sculptures the conservation of the physical form of the chocolate is complex and difficult due to the inherent nature of the material which readily changes due to chemical and biological processes. At the same time, however, such art works may have been made with the very intention that they should decay, with this mutability and alteration of the material part of the message communicated by the artist. The conservator is thus faced with a dilemma between preserving the physical form of the object or allowing it to physically alter, and perhaps disappear altogether, but thus prioritising the concept of the artist.

In the case of doped-fabric aircraft, one issue in this regard is the value of the objects as static, unmoving museum displays. Without ever actually seeing these aircraft fly, or indeed flying inside them oneself, and thus experiencing the emotions, feelings and sensations which may be bound up with such processes, an important aspect of these objects is lost. The existence of various flying clubs to restore and replicate such historic machines to working order demonstrates that such values remain important to certain groups.

4.1.2. The Nature of Deterioration, Change and Authenticity

The manner in which one perceives changes to objects, and whether certain processes are considered positive or negative, may not be consistent in all cases and vary from context to context. Corrosion, tarnish and patina, for example, represent much the same processes taking place to the physical condition of an object. The terms corroded and tarnished, however, may generally be understood to represent a deterioration in condition, whilst patinated may be a less loaded term and even signify a potential improvement in appearance, and is thus a process which can enhance and add to the value of an object.

Even quite dramatic change may be considered in some senses to enhance an object's value. An incomplete, broken archaeological ceramic on display in a museum, for example, may derive much of its value from the very fact that it is damaged and that a museum visitor might interpret this as signs of age and proof of its being an authentic historic object. As such signs of its history, including breaks, chips and wear, can be what make an object of interest in the present, yet these same features might have made such an object worthless to its producer or previous owners if it was expected to be whole and as new.

Objects can thus be recreated in ways that different users may not expect or foresee as different value systems prioritise different aspects of an object, turning deterioration into value and value into deterioration. There is evidence, for example, that Greek statues were often very brightly painted and ornate, and could be augmented with clothing and other props (Brinkmann, Potts and Collareta, 2008). Such statues would then be used in processions and other ritual events as almost working, living objects. This is a very different interpretation and use of such objects compared to their place in many contemporary museums. A walk through the Greek sculpture gallery at the British Museum presents such objects as gleaming white, crisp marble art works. Such objects have thus been changed significantly to fit into a very different value system and it is not clear which presentation, if either, is 'correct' or 'false'. Such a judgement would require a pre-conception as to what such objects are for and how they should be used, and so evaluation of their change in appearance from decorated statue to museum marble is thus one of personal taste and evaluation.

The concept of value and significance, therefore, are fundamental to how change is perceived and hence whether it is judged a negative or a positive alteration. Such judgements are highly contextual, and the same object may be read in different ways depending upon a whole range of factors, such as the aesthetics of the period, the context in which it is displayed and how its history and purpose is presented.

Such differing value systems have already appeared in this thesis. As already noted in discussions about the Supermarine S6B (Chapter 3.1.3), letters from the public have commented and complained about its condition and appearance, believing it to not be original in appearance and the victim of a badly executed restoration paint job and subsequent neglect. Such views may have in part been formed because of the contrast of the Science Museum aircraft to another similar machine on display in Southampton in a very different state of repair and restoration.

Research into the paint, however, by the curators indicates that the paint may well be original, although of course this does not necessarily entail that the machine still looks as it did when first flown as such materials may visibly alter and wear over time. There is thus a divide between the aesthetic and historic values in this

instance and ultimately no way to prove one set as correct and the other false. The fact that the aircraft has not been restored as suggested by the members of the public is probably due to its location in a museum where historical attributes of objects are often at the forefront of decision making (though availability of resources and other practical factors around how conservation is managed and implemented in a museum context may also play their part! (Keene, 2002)).

There are even cases where what appears to be clear deterioration may also be valued. The hole punched in the Vickers Vimy wing by a visitor, for example, whilst at first appearance a clear sign of damage, could have had a value in visitor education as to how vulnerable such objects are to human touching. If the alteration had been caused by some notable figure, moreover, or with a clear artistic or political protest message behind it, for example, we should consider if this might also change how such damage is viewed.

4.1.3. Authority and Decision Making

As discussed above the values understood in an object by one individual or group, may be completely different and at odds to those of another individual or group, such that finding compromise between these different perspectives is very challenging, perhaps impossible. This leads to the issue as to who has the authority and power to control heritage and decide how it is conserved, and this has been especially evident in cases involving the interactions of different cultural groups (Krmopotich and Peers, 2013; Atkinson, 2016). In the Americas, for example, the management of heritage related to First Peoples has proved a contentious issue, and provides a useful case as to how power and authority can influence conservation decision making processes (Drumheller and Kaminitz, 1994).

Traditionally, such heritage was treated by conservators with very little input from the cultural groups from which it originated (Clavir, 2002). As such the materiality of the object, and maintaining it physically for future generations within the museum context in line with tangible values was usually at the forefront of conservation thinking. The concerns, thoughts and views of the First Nation Peoples, who at times wished to use or interact with such heritage, which they viewed as theirs, beyond the museum were overlooked in such discussions.

Changes in social and cultural attitudes, however, have led to a rethink of how such heritage is managed, and some museums now make greater efforts to involve First Nation Communities in their work (Matero, 2004; Fforde, 2009). This change is driven in part by legal changes, such as the North American Grave Repatriation Act (NAGPRA), which requires cultural institutions in the USA to make lists of their collections related to Indigenous Peoples available and repatriate objects in certain instances (American Indian Liason Office, 2012).

It also reflects a change in heritage management, however, which increasingly acknowledges that expertise and authority do not only reside with museum professionals. Instead museums and cultural institutions increasingly recognise that they must work with other groups to effectively manage their collections and realise their full significance. Some institutions housing First Nation People objects, for example, now work with the communities in caring for the objects to ensure that they are appropriately stored to their cultural standards, not just museum environmental ones.

In terms of doped-fabric aircraft, there are certain groups who might see the restoration of such objects to flying condition or appearance as the greatest priority, and who would consequently probably significantly alter the look of the objects currently housed at the museum if given the opportunity. Such voices are unlikely to have much direct influence at the Science Museum in the near future, however, where such decisions appear still largely at the discretion of conservators, curators and other museum staff.

4.2. The Principles and Ethics of Conservation

There are number of common ethical themes and ideas shared across conservation as a profession which it is important to discuss here, as they have a major impact on the approach conservators make to their work. They are a key bedrock by which conservation work is judged and considered, and which many conservators will almost unconsciously refer to when assessing objects. A review of conservation history and practice, however, such as that offered by the Readings in Conservation series published by the Getty, shows that the implementation of these principles and concepts is very subjective and can vary greatly over time and geographically, yet their impact upon the profession cannot be underestimated (Stanley-Price, Talley and Melucco Vaccaro, 1996; Bomford, Leonard and Institute., 2004; Brooks and Eastop, 2011).

4.2.1. Minimum Intervention

The principle of minimum intervention seeks to limit the extent that conservators alter or change an object and implies that conservators should therefore do no more to an object than necessary to achieve a desired outcome. This has tended to apply principally to the physical material of the object in terms of its tangible qualities, restricting the impact of conservation work on the original material or physical qualities of an object.

The concept of minimum intervention consequently acts as a brake on conservators' actions, challenging them to think through the potential consequences of their decisions, and justify whether an action is necessary. Ideally, the process of questioning the necessity of actions should also make conservators engage with the issue

of why it is necessary and challenge automatic rote-learned responses about what needs to be done and why, in line with questions about value and significance discussed above.

The very existence of such a principle, however, implies something about how conservation understands its role in heritage management as maintaining heritage as a truthful or 'authentic' resource. When thinking about the opposite of minimum intervention, and the consequences of going beyond the minimum, there is presumably a negative impact with unwanted outcomes in doing too much. These negative consequences indicate a concern with artificially altering an object, creating a heritage that never truly existed and thus subverting the authenticity of the material being treated.

The concept of minimum intervention is a difficult principle to interpret and apply consistently across an entire profession or individual's work as there is no single definition as what constitutes a minimum level of, or indeed even what an intervention is. Carried to one extreme the concept indicates that conservators should not treat objects in any manner, perhaps even so far as not providing appropriate storage conditions and packaging, or advice about their care.

The term minimum intervention, therefore, does not provide a hard and fast rule or objective yard stick by which the quality of conservation treatments or interventions may be measured. It is, rather, an ethical concept which imparts professional caution and critical reflection when applied properly.

4.2.2. Reversibility/Re-treatability

The ideas of reversibility and re-treatability are in some respects intimately linked with minimum intervention, and are very deeply rooted in the heritage conservation profession. These two principles are largely synonymous, although are subtly different in terms of how they illustrate conservation thinking. At the root of both is the concept that any work undertaken by conservators should not result in permanent, unalterable consequences for the treated object.

Reversibility implies any intervention should be fully removable, so that no evidence of the treatment remains. This might involve deconstructing an object or removing any added materials, such as fills, adhesives and in-paintings. As materials age, however, chemical changes can occur which mean that they become very hard to chemically soften or mechanically clean, which can result in them becoming permanently bonded to an object. Equally, applying a material chemically similar to a heritage object can result in difficulties if attempting to remove it since whatever solvents may be used to remove the conservation material are more likely to interact with the heritage object.

A great deal of conservation activity is therefore directed at avoiding these problems. Key questions involve researching which adhesives and other conservation products are most stable under museum conditions and unlikely to chemically alter in an undesired manner (Down *et al.*, 1996; Horie, 2010; Down, 2015). Equally important is understanding the chemistry of objects being treated to avoid applying materials which will almost certainly react in such a way that their later removal becomes very difficult if not impossible without significantly altering the nature of the heritage object.

The alternative term re-treatability, has begun to enter use in part due to a recognition in the conservation profession that no process can be considered totally reversible (Pye, 2001). When deconstructing a break join previously adhered together some changes, whether chemical or physical, will result if only at a microscopic scale. No treatment can ever be fully removed, moreover, since microscopic traces of the materials used will always remain on the surface. Even conceptually reversal can be difficult as conservation treatments can recreate how an object looks and feels to an audience, and it can be very difficult to then change this mindset if an alternative presentation is considered more appropriate in the future.

The concept re-treatability has important implications, since it acknowledges that the present moment is not necessarily the most important point of an object's life, but that it will have a future as well in which very different ideas and values for an object may be considered more important. Whilst not all such eventualities may be foreseen or predicted, the process of thinking these questions through is of great value since, as with minimum intervention, it requires conservation professionals to stop and critically engage with the potential consequences of their work.

4.2.3. Integrity

The term integrity is difficult to define, embodying a range of ideas and principles and is in part concerned with ensuring that conservation should not re-invent an object. An object is essentially what it is, and whilst conservation may enhance certain features (whilst simultaneously destroying others), it should not invent these features.

One aspect of this is the problem of how new materials or repairs should be distinguished from the pre-existing fabric of an object (use of the term original is purposefully avoided in the preceding sentence as this carries its own implicit assumptions about authenticity and value). The aim of distinguishing materials from a conservation treatment is to ensure that any work undertaken by conservators should be identifiable when necessary, and this concept aims to prevent viewers of the object from being misled in their interpretation of what is 'original' or 'authentic' to an object.

When viewing a reconstructed archaeological ceramic, for example, it is common for material to have been lost and for these gaps to be filled with new material which could be made indistinguishable from the surrounding material. This may assist in the aesthetic appeal of the object as it appears whole and the form is easy to see. In contrast, within an academic study it may be problematic if original and filled material parts cannot be separated when only the archaeological material is of interest, and it can mislead viewers as to how much of an object was actually recovered.

A further concern in this respect is that conservators should be wary of how far they impose their own interpretations of objects onto them. This is again to prevent misinterpretations and misunderstandings of objects taking place. A reconstruction, for example, may require some guess work as to the shape of an object, or where certain parts may be fitted. Such work requires very careful consideration as mistakes can have serious consequences for long-term readings and interpretations of an object.

In the case of the doped-fabric aircraft, therefore, where so much intervention has taken place, careful thought must be given as to how much is actually known about how such objects would look or operate and what form aircraft would actually be returned to by re-covering. If a re-covering were carried out, for example, information available about how it should be done would be available from the current covering condition and potential historic and literature sources. This would place great faith, however, that the subsequent coverings were accurate, and that the historic sources accurately represent the quality and methods used in producing such objects which, as discussed in chapter 2, may not always be the case. Whether the objects can thus ever be considered authentic, original or to have integrity may always be a matter open to interpretation.

4.2.4. Documentation

Documentation is important so that the actions of conservators may be distinguished clearly from the rest of the object (Caple, 2009; Kemp, 2009). Where available this makes interpretations of objects much more straightforward, as the path by which an object evolved may be reconstructed. This enables determinations about the value, significance and authenticity of the different aspects of an object to be more meaningfully judged.

It is not uncommon to encounter objects with clear signs of treatments, yet for which no documentation has been kept and no information as to when or why changes were made, as already seen from the review of the doped-fabric aircraft technical files kept at the Science Museum. Indeed changes to an object may not even be recognised as such if no record of their taking place is kept, and the Canadian Conservation Institute (CCI) has

identified problems in the management of collections and documentation as one of its ten agents of deterioration; *dissociation* (CCI, 2017).

Documenting conservation work is therefore vital in order that interventions made by conservators are not forgotten or misinterpreted, leading to future confusion. The two most important reports produced include the condition report, which documents an objects state at a point in time, and the conservation record, which records any work undertaken.

4.2.5. Conservation and Restoration

Considering the distinction between conservation and restoration provides a useful context in which to summarise and emphasise what defines conservation as a profession. The two terms are often conflated together and used interchangeably, which may be justified in certain situations as the two processes can appear very similar (Vinas, 2005). Both processes may involve certain practices, such as cleaning, replacement of damaged areas and the concealment of various defects.

Where the two processes are markedly different, however, is in the underlying ethos and principles which drive and direct them. As has been shown in the foregoing discussion, conservation as a profession relies upon self-reflection and self-criticism for validity and integrity. If there are no indications that the wider ethical implications of a conservation treatment, in terms of how it might impact an object's significance, value, authenticity or integrity, has been considered, then an intervention cannot be considered as conservation.

A restoration, in contrast, as its very name implies, begins from the viewpoint of returning an object to some prior condition. The veracity of this restored condition will depend upon the pre-conceptions, quality, skill and availability of information to those undertaking the work. Regardless of how well the restoration is undertaken, however, it cannot be considered conservation if the work is not considered within a wider conservation framework of ethics and standards.

Conservation and restoration, therefore, are not necessarily distinguishable in terms of the actions or treatments undertaken. The same outcome may eventuate when treating the same object whether done as a restoration or conservation treatment. The distinction arises, however, because for the conservation treatment a wider range of options and ethical issues will require considering which may involve leaving signs of damage or previous interventions in place if these are deemed to have value.

4.3. Summarising the Process of Conservation

What the chapter has demonstrated is that there is an overarching ethical framework through which conservation as a profession attempts to direct and control its practices and processes. This does not mean that there will be universal agreement upon the quality, necessity or sensitivity of a particular treatment approach but that the treatment may be assessed and critiqued according to a shared set of values and ideas. This paper suggests that conservation may be split into five broad stages based on the foregoing discussion:

- **Significance and Value:** Conservation must begin with an assessment of an objects value and significance which seeks to be open and impartial. The ease and extent to which this can be done is not fixed and will differ depending upon the characters of the societies, cultures, organisations and individuals involved. Once the values and significance of an object are identified, they may then be compared and evaluated to determine which features of an object are of most concern and importance for conservation treatment.
- **Treatment Purpose:** It is only after the values and significance of an object is understood, and which are of most importance, that the purpose of any treatment be considered. This stage is the point at which to think various outcomes through, to consider if given a perfect world, what should the final treatment outcome look like and what would its long-term consequences for an object entail.
- **Treatment Selection:** The third stage of conservation should then be a treatment selection. This is the point at which the actual practicalities of what is possible, given the materials and resources available, are considered. At this stage the treatments may be evaluated in terms of various conservation principles, such as minimum intervention and re-treatability.
- **Treatment and Documentation:** The final stage of conservation is then application of the treatment and documentation of it. It is important to emphasise that this step is no more important than any of the preceding stages. It is often the part most people would begin thinking about initially and consider as defining the success of a conservation treatment, but it is only one part of the conservation process. Regardless of how well an intervention is applied, if it is the wrong decision due to poor evaluation during the preceding steps, the quality of the conservation process will be diminished.
- **Treatment Evaluation:** A complete conservation process would ideally involve a periodic inspection and re-evaluation of treatments to assess how well they are performing in terms of all the stages listed above. This stage unfortunately is rarely conducted due to resource pressures and demands.

Conservation, therefore, is not so much about the specific treatment, but the process through which a treatment is decided upon and determined to be most suitable. This potentially requires input from many different sources at each stage, and may prove to be a highly complex, inter-disciplinary process.

4.4. Current Practice in Museums Relating to Doped-Fabric Conservation

Due to a lack of published literature regarding specific treatments of tears in doped-fabric aircraft, contact was made with a range of institutions to learn more about their approach to the conservation of doped-fabric. This involved direct approaches to several institutions identified of interest from the literature available as well as a general query sent to a conservation online forum known as the ConsDistList. Responses were received from conservators at the Smithsonian National Air and Space Museum in Washington D.C, the National Museum of Flight in Scotland, The Australian War Memorial (AWM) in Canberra Australia, and the Henry Ford Museum in Dear Park USA. The author also visited the RAF Museum Cosford to meet the doped-fabric technicians working there, to talk through and see the materials and techniques used first hand. The information gathered through this correspondence and visits will be presented here.

Technicians at the RAF Cosford Museum recommended the use of a doped-fabric patch much as is currently in use at the Science Museum for stabilising tears in doped-fabric skins (Rose Pers. Comm²). They also recommended in more extreme cases of damage, either due to a very large tear or due to excessive numbers of patches cutting out the panel and inserting a new one, such as was discussed in the maintenance repair methods section (Chapter 2.3.3).

The RAF Museum Cosford, therefore, appears to adopt traditional repair techniques in maintaining its historic doped-fabric aircraft, most of which seem to have been re-covered recently from discussion with the technicians. The aesthetic of the aircraft for display, therefore, seems of most importance within this institution when determining treatment options and approaches. This was apparent on a walk through the galleries where most aircraft appeared to be in an 'as new' condition.

The technicians had an excellent knowledge of the practical skills and techniques of constructing and restoring historic aircraft, often coming from engineering and mechanics backgrounds. They also had an excellent store of historic tools, materials and reference samples, many of which would likely prove difficult to source today or would need to be specially commissioned. The availability of specialist resources, such as a doping room, also enables the team at Cosford to undertake large scale works not necessarily possible elsewhere. During the visit,

² Site visit by author to RAF Museum Cosford, on 16/04/2015

the project being worked on was recovering of the wings from a Wellington bomber; the size of even one of these wings would make moving it through the Science Museum a major logistical challenge, and finding a space to store and work on it virtually impossible.

A response from AWM advised in the case of small holes (about the size of a ball point pen) the use of Japanese tissue paper with carboxymethyl cellulose to patch over the damage (Bailey Pers.Comm³). In the case of larger holes, however, it was advised to use traditional methods by first sewing to draw the tear edges together, followed by use of a cellulose nitrate dope patch. As at the Science Museum, diluting the first coat of dope 50/50 in in dope thinners was advised to soften the dope substrate and improve bonding, and cellulose nitrate over cellulose acetate dopes were recommended due to longer-term shrinkage issues of acetates not found with nitrates. This issue of long-term dope shrinking is an important one in the conservation of doped-fabric aircraft and is treated in more depth in section 4.5.3.

The Aircraft and Technology Conservator at the National Museum of Flight in Scotland provided details of a tear repair conducted on a Kay Autogiro in 2011 (Bürgel Pers. Comm⁴). In this instance, rather than using traditional materials, i.e. aircraft linen and dope, polyamide gauze was used in place of linen, and Lascaux 4176 consolidation medium in place of dope. The patch was then coloured in using watercolours (aquarelle) in Lascaux 4176. The reasoning behind choosing polyamide gauze and Lascaux 4176 was to avoid potential long-term shrinking problems attributed to cellulose nitrate materials, and so that the treatment could be removed without affecting the underlying doped-fabric, presumably as the Lascaux 4176 will be re-solubilised in different solvents to the dope. The use of dopes was also avoided so as not to re-soften the historic dope film under treatment.

A response from the Henry Ford Museum, in Dearborn USA provided details of a treatment carried out in 1986 for a tear in the Josephine Ford Trimotor aircraft (Nguyen Pers. Comm⁵). Two tears had been opening in the side of the aircraft fuselage where two seams of fabric met, and at time of treatment the shorter tear was thought to be growing at a rate of approximately 2.5cm per month. FTIR analysis contained in the report identified the dope as a cellulose butyrate. The conservators attribute the damage primarily to the problem of on-going shrinkage in the cellulose butyrate dope though other potential contributing factors identified included environmental conditions, such as cycling RH and light exposure, as well as historic maintenance practices, such as the use of solvent based cleaning products on the paints.

³ Email received 16/03/2015

⁴ Email received 31/03/2015

⁵ Email received 29/02/2016

The treatment described is an adaptation of paintings conservation techniques. Velcro systems of support were designed to first re-align the fabric edges. This involved an initial support system on the exterior which was attached using bull dog clips, during which the lower fabric was re-shaped having been plastically deformed after years of sagging. The doped-fabric and paint were softened using heat whilst being reshaped. A second Velcro support system was then attached to the interior, in which Velcro was stitched to muslin backing and adhered above and below the tear. The fixings of the doped-fabric to the frame were in places released to allow for re-positioning of the fabric.

With access to the interior, the conservators opted to line the edges of the tear to hold it together. The lining material chosen was polyester sailcloth impregnated with Beva 371, a heat activated adhesive meaning no water or solvents are required to use it. The conservators chose this as during tests and adhesion of the Velcro straps to the canvas, it was noted that the fabric and paint were sensitive to water and solvents. The other advantages ascribed to it are that it does not impregnate the material, forming a bond with the canvas napping at the surface, and that it is relatively inert to changes in RH. The concept of lining, and the research undertaken in this area is treated in more depth in chapter 5.

The lining fabric was first attached to the lower edge of the fabric by heating it using a portable hot plate held against the inside, whilst pressure was applied against the other by hand. The top section was then adhered in place again by pushing against the exterior by hand, whilst the interior adhesive-lining side was activated using aluminium plates heated with tacking irons. Where gaps remained, the conservators state they were filled with pigmented micro-crystalline wax.

The idea of adapting paintings conservation techniques has also been explored at the National Air and Space Museum in a treatment undertaken on the elevator of a B-26 Marauder (Horelick Pers. Comm⁶). The original fabric of the elevator had significantly deteriorated, with numerous tears running across it and patches from previous repairs undertaken. A treatment was designed to retain the original fabric in which the fabric was first removed from the elevator frame by backing it with Reemay (spun polyester textile) so that it would retain its original tension when lifted. Once separated from the frame, the curled edges of tears could be relaxed using a solvent atmosphere and weights.

Ceconite fabric was then used to re-cover the elevator structure and Beva 371b adhesive to re-adhere the original fabric onto this new Ceconite support using a heated spatula. After this, areas of loss were filled with Beva Gesso before inpainting. The result was the retention of the original fabric, with various signs of its age and

⁶ Email received 11/04/2017

history, whilst the significant areas of structural damage were no longer visible and stabilised. This appears to have been an effective treatment for returning the control surface to a display ready condition whilst retaining original material without opting for a full restoration. It should be noted, however, that the treatment was time consuming, taking three years from initial inspection to completion and does still require considerable space, though given the ability to remove the control surface from the aircraft is possible in a modest sized conservation space.

There therefore seems to be a mix of different approaches and attitudes in doped-fabric skin conservation from the use of traditional maintenance techniques, through to the adaptation of knowledge and techniques from other conservation knowledge fields, most notably that of canvas paintings. What is notable about the treatments adapted from paintings, however, is that in both instances access to the interior surfaces was available. Such good access is not always possible, however, especially when working on doped-fabric aircraft wings which are sealed. This limits the pressure that can be exerted when only one side is reachable, making the use of heat seal adhesives very difficult, as found by Beesley (Beesley, 2009).

4.5. The Conservation of Doped-Fabric Aircraft in Museum Contexts

4.5.1. Conservation or Restoration

This literature review will explore how doped-fabric aircraft are managed in museums and how their conservation encompasses many of the issues discussed earlier in this chapter regarding conservation more generally. These issues involve concerns such as the balance between conservation and restoration, the application and interpretation of conservation ethics, for example minimum intervention, and debates about who, how and why treatments are decided upon. In addition to these themes, this section of the literature review will also demonstrate the level of knowledge regarding doped-fabric as a material, and the amount of research conducted to understand its material properties.

Much of the literature on doped-fabric aircraft in museum tends to treat aircraft as restoration projects or falls into a grey area where the distinction between conservation and restoration is blurred. One of the largest works on the management of aircraft in museums is *Restoring Museum Aircraft* by R.Mikesh, a former senior curator at the National Air and Space Museum (NASM) (Mikesh, 1997). This publication discusses the work of the NASM in caring for its collection and, as the title suggests, unapologetically champions a restoration approach, detailing many of the projects undertaken to return aircraft in the collection to a perceived former condition.

This is not intended as a criticism of the quality of craftsmanship and engineering that the book describes. Indeed, the care and attention to detail described in many of the projects, such as the careful annotated photo documentation of paints and markings on an Fw 190F-8 (Chapter 8) and paint on a P-51C Excalibur III (Chapter 9), would be considered good practice in a conservation project. The book acknowledges in places, moreover, that full restorations are not always the right option and that conservation professionals can play an important role in aircraft preservation (Chapter 1).

What makes it clear that the author's interest is in restoration and not conservation, however, and comes across throughout the publication, is a pre-occupation with what the aircraft once were (or were envisaged to have been) in the past, rather than what they were in that present moment of decision making. Anything that suggested deterioration, or which might distract the observer from understanding the object as an airworthy aircraft, is in most instances considered unacceptable without consideration as to how such signs might fit into other values and stories of the aircraft, such as its history and use.

A project describing the management of the Domenjot Bleriot XI in Chapter 4, for example, initially sought to retain the original doped-fabric of the aircraft in-situ as the aircraft was believed to be in good condition, only requiring light cleaning and other minor work. On closer inspection, however, when deterioration of the interior framework was found, the technicians began to manage this interior deterioration by removing individual pieces where accessible and treating them before re-instating them, so as to avoid disturbing the original doped-fabric skin.

When Mikesch learned of this approach, however, which he felt to be 'a half-way restoration' instead of the straightforward touch up as originally planned, he pushed for a complete restoration instead which entailed completely removing the fabric, rebuilding and treating the interior structure, and then re-covering it with a new doped-fabric skin. The justification was given as 'not only was this simpler, but the life expectancy of this valued artefact was greatly improved' (p.63), although seemingly at the expense of effectively renewing it rather than extending the age of existing components.

It is of course difficult to judge the necessity or otherwise of this full-restoration not having seen the object first hand. Where this restoration diverges from conservation, however, is that based on conservation ethics and principles it seems likely that conservators would have been more accepting of the interior deterioration. This is not to say a conservator would not take any action over the interior, but that the 'half-way' approach previously described by Mikesch, in which some continued deterioration is accepted to retain the object as is, with its signs of use, history and some deterioration, would have probably proved acceptable. As discussed earlier,

conservation is as much about managing how deterioration is understood, as it is about reversing or hiding the signs of it.

What is perhaps most worrying for a conservation practitioner regarding this particular project might be Mikesch's concluding comments on the project in which he states, 'Perhaps the success or failure of retaining the originality of an aircraft can best be measured by a look in the waste container at the conclusion of the restoration and evaluating *how much of the original and highly valued aircraft has been thrown out with the trash*' (p.65, (Italics are as printed in the text)). It is hoped that this comment is being made in a tongue and cheek manner, but it also epitomises the contradiction at the heart of many restoration (and conservation) projects in which much of what is physically original may be lost to restore a look and feel that is believed more original.

Mikesch's attitude is best exemplified in a comparison he makes of treatments for a Spad XIII at NASM and Spad VII at Musee de L'Air et de l'Espace in France. The French treatment involved preservation of the original doped-fabric in place on the airframe by adapting a lining painting conservation technique. In this process the fabric was mounted onto support fabric panels which were then attached to the airframe. Mikesch notes that he 'found this appearance to be distracting from what the airplane itself was meant to convey to me as the viewer' (p.83).

The NASM approach to their Spad XIII, in contrast, involved a complete replacement of the original fabric, which was then stored in a custom-built box. Mikesch acknowledges that this resulted in an aircraft that appeared far too new to have ever been in combat, as the Spad XIII had been in use during WWI, but which retained the correct appearance to his eye in terms of the lines and finish of the fabric. There are, therefore, two seemingly incompatible concerns, originality of appearance, which seems difficult to ever restore in reality given the problems replicating the look of an aircraft after an active life, and originality of materials, the retention of which may require compromise in how the aircraft looks in terms of finished lines and satisfying aesthetic expectations of certain viewers.

It is useful to consider why Mikesch focuses on restoration, and consequently made the choices he did and prioritised certain attributes of the aircraft in his care over others. This focus on restoration is perhaps a reflection of Mikesch's background as a former US Navy pilot and keen model maker, aspects of his life he discusses in the about the author section, and therefore someone accustomed to working with and being around aircraft in working condition.

McManus writing around the same time, but in striking contrast to Mikesch, is highly critical of the restoration culture he identifies in aviation collections. McManus's main criticism is against the attitude of restorers, arguing

that the approach taken is often more about self-serving interest, namely satisfying a personal desire to see the aircraft in a 'pristine' condition as the restorers imagine it, rather than adhering to any sort of historic reality as to how the aircraft may have ever looked or functioned in reality (Mcmanus, 1994).

In McManus' view, restoration of historic aircraft in museum contexts, therefore, when judged by conservation standards, is usually the wrong approach because they are not carried out in line with any sort of ethical or theoretical framework. Restoration more often results in falsified objects, where aircraft are over embellished and too much liberty is taken by restorers in returning them to a level of perfection which likely never existed. McManus is also critical of restorations which he claims have re-invented aircraft by changing or reconfiguring them so that they evoke individual famous planes or squadrons with which the actual aircraft being treated was never associated.

McManus' main thrust, therefore, seems to be that whereas conservation deals with an object as received, staying true to its individual history and object biography, aircraft restorers have been more prone to deal with the object they wished they'd received, which can involve significant invention and imagination to create. From a museum conservation perspective, these criticisms appear strong and well-grounded since such invention is not permissible under most published ethics and guidelines and would significantly undermine the integrity of an object.

McManus, however, is careful not to claim that all aircraft should be left untouched or untreated, and states that restoration is not necessarily the wrong choice. He acknowledges that restoration to flying condition can be a good thing in certain circumstances where sufficient material in good enough condition exists, or indeed so little that the object is more re-built than restored. What McManus seems to be advocating for, therefore, is a greater role for conservation thinking, ethics and practices, within aviation museum environments in terms of determining how and why one treatment approach might be more appropriate than others.

For McManus this means properly documenting how and why an object is important, ensuring that all work is properly recorded. The originality of the aircraft itself, and the limitations as to what is known about how it might have looked and functioned, need also to be acknowledged and act as restraints upon the amount of work carried out.

Staelens and Morris in their consideration of how large heritage objects are conserved draw out similar themes to McManus, but apportion the blame for poor restorations largely to the heritage and conservation industry (Staelens and Morris, 2010). They argue that industrial technology museums and collections tend to develop as independent, private concerns developed by enthusiasts and individuals with a passion for the subject, and are

consequently often handicapped, lacking the funds, support or resources available to larger, more traditional and established museum institutions. The fact that such collections are left to the care of amateur enthusiasts who are not familiar with conservation ethics, therefore, is as much a fault of the heritage and conservation world, which prefers to focus its resources on training and research in other areas, such as archaeology, ethnography and fine art.

A further important matter that Staelens and Morris address, is why the originality of material in these industrial objects matters. This is a consideration that can often be taken for granted, and one that McManus does not adequately deal with in his own critique of aircraft restoration. Staelens and Morris write,

From a sustainable viewpoint, if objects are to retain heritage value then they need to be capable of interpretation and reinterpretation. This relies upon the survival and quality of data inherent in their fabric and upon their cultural biography. If the object has been stripped of original features in a mission to reactivate it, then its sustainability as a heritage object has been compromised and minimised. ... It is curious that such actions would not be tolerated with regard to other types of collections for example furniture, fine art or archaeology. So the question remains, why are large working objects treated differently? (Staelens & Morris 2010, 1186)

This is not to say that there has been no effort at all on the part of the heritage sector to engage with industrial collections and introduce conservation concepts into management of such collections. The British Aviation Preservation Council, in conjunction with Imperial War Museum (IWM), Duxford, for example, established the National Aviation Heritage Skills Initiative programme. This was a five year, Heritage Lottery Funded (HLF) programme run from 2006 to 2011 to train non-museum professionals in the care of aviation heritage.

The training notes from the doped-fabric section of a course as part of this training present many of the practical skills and techniques needed to repair a doped-fabric skin, but also remind the participants to question how and why they are making decisions (National Aviation Heritage Skills Initiative, no date). One of the first themes discussed is entitled 'Considerations' which begins by challenging readers to first consider why they have decided it necessary to undertake a re-covering project to begin with and if other options may be possible. The text also emphasises the importance of recording work carried out and not inventing details if it all possible.

A final theme which it is worth considering is the broader context of aviation conservation, and not just that within museums. During the 1990's in the USA, for example, there appears to have been increased emphasis and encouragement for individuals and organisations to register historic sites associated with aircraft with The National Register of Historic Places (National Park Service, 1997a; Milbrooke *et al.*, 1998). This register is a list of 'districts, sites, buildings, structures, and objects significant' to the USA. Objects listed can therefore range from

an individual aircraft (such as the 1905 Wright Flier added in 1991), to a complex of buildings, and can have a wide range of connections to aviation spanning research, production, airfields, crash sites etc.

The influence of a process such as the National Registry in historic aviation may be important since it again changes the mental attitude of those involved in the process (Diebold *et al.*, 1993). For a start it requires a form to be filled in which requires engagement with many fundamental questions about the heritage, such as why it is important through a statement of significance, to describe it, document it and put it into a historical context. A national register, moreover, groups objects and begins to show the extent (or lack thereof) of a particular type of heritage and the wider context within which these items sit.

The National Parks Service, moreover, provided guidance on how this form should be filled in. A specific publication was made to support the heritage aviation sector in this work, *National Register Bulletin: Guidelines for Evaluating and Documenting Historic Aviation Properties* (National Park Service, 1997b). This document provides guidelines about how to approach heritage when thinking about why it matters, to assess its condition and, importantly, potential future significance.

Although museum objects are automatically excluded from the National Register (they are already considered taken care of), the introduction of these documents into aviation heritage does signal that heritage ideas have gained more ground in the management of aviation heritage (at least in some places), introducing and defining concepts, such as significance, integrity, originality and authenticity, in a field that previously seemed largely devoid of such concerns.

4.5.2. Conservation Treatments of Aircraft in Museums

This section will provide details of treatments and discussions of doped-fabric aircraft described in the conservation literature. Most are taken from peer-reviewed sources, though it should be noted that a few originate from blog posts and other similar unreviewed sources, which will be made clear when relevant. Such sources, although not ideal for use in academic study, are of relevance here as these still provide evidence as to the types of discussions taking place in conservation circles about doped-fabric and represent sources of information used by conservators when investigating such materials.

One very interesting case study is the treatment of a Corsair KD431 at the Fleet Air Arm Museum (FAAM) in Yeovilton (Staelens and Morris, 2010). This aircraft had undergone extensive re-painting in the 1963 when accessioned by the FAAM to make it presentable for display by the standards of the time. Morris, the curator at FAAM and his team decided to undertake exploratory work in 2000 into whether the original paint survived

beneath the 1960's restoration. It was found that paint was still present below the 1960's material, and so a project to painstakingly remove the entire 1960's layer back to the earlier surface was undertaken.

What is striking about this project is, as the authors points out, that this Corsair is now one of the most significant one of its kind in the world as it is the only known one on which the original paint work can still be seen. It is not only paintwork, moreover, but other signs of use from history, such as 'scuffs of aviator's boots, the maintenance engineers' scratches and rough paint marking' (Staelens & Morris 2010, 1187). These are the things which no restoration can ever restore because they are totally unique to the life and historic material of the object.

Finally, the project was carried out by museum volunteers, not museum professionals, demonstrating that conservation does not necessarily have to be at odds with the involvement of volunteers and aviation enthusiasts. Staelens and Morris therefore find some balance between the tension of Mikeshe's focus on restoration and McManus's arguments for conservation. They demonstrate that when museum professional's do engage with aviation heritage, and work with aviation enthusiasts discussing how and why certain approaches may or may not be appropriate, then positive outcomes can occur.

Another conservation process is described by Horelick at the NASM in a 2013 treatment of a Horten Ho 229V3, an aircraft formed of a steel interior frame clad with a plywood skin which had significantly deteriorated due to poor museum storage conditions over several decades (Horelick, 2015). From Horelick's account it appears that working attitudes have changed somewhat since Mikeshe worked as curator at NASM, as despite calls from enthusiasts for a full restoration, it was determined that the deterioration itself was part of the Horten's history even though it happened since entering the museum collection, and that a full restoration was uncalled for given the existence of several other reproductions and copies outside the museum.

The conservation team were working with a retired restoration technician from the NASM who volunteered on the project. Horelick notes the very different approaches taken by the conservators, who tended to be much more hesitant in undertaking any actions compared to the restoration technician who was bemused by the cautious attitude of conservators. The former NASM technician, for instance, accustomed to working with aircraft as a mechanic advocated the disassembly of the aircraft's plywood skin and structure, a process he assumed would be the natural first step in the project. The conservation team, however, initially resisted this process as too invasive and risky though eventually agreed that disassembly was the appropriate approach, and Horelick acknowledges this proved of great worth for enabling better access to damaged sections both for documentation and treatment.

Despite this highly interventive step of dismantling the aircraft, minimum intervention was still important to the conservation team to lessen the impact on the originality of the aircraft and so traditional aircraft repair techniques were adapted for the conservation work. Areas of damaged plywood skin, for example, are traditionally replaced using a technique known as scarfing, when deteriorated plywood is cut out along with a section of undeteriorated material, to create a stable surface onto which new plywood can be bonded.

For the Horton, however, after trials on mocked up samples, it was decided that such an extensive approach was unnecessary, and that the damaged plywood could be pared back only a few centimetres, the edges consolidated with a resin, and that this created a good enough surface onto which new plywood skin could be joined. This repair technique, therefore, represents a compromise between traditional practice and conservation attitudes whereby the necessary extent of treatments are questioned and adapted as necessary.

Firth describes another treatment project, which she states involved a collaboration between conservation professionals at the Australian War Memorial (AWM) in Canberra and members of an organisation called the Memorial Flight Association in France who build airworthy replicas of historic aircraft (Firth, 2009). In this case, a decision was made to re-place the doped-fabric skins of two AWM aircraft, an Albatros D.Va and Pfalz D.XII.

Significant interventions in treatment of the skins was considered necessary in these instances as previous restorations during the 1960's and 1970's had resulted in what were considered inaccurate, poor results. This was partly because a special pre-dyed fabric, known as lozenge pattern, was not available for re-covering of the Pfalz D.XII such as would have originally been used, and due to the application of a clear cellulose butyrate dope which was believed to have carried on shrinking over many years causing distortion of the underlying framework (Pearce, 2004).

The fabric removed during the 1960's and 1970's treatments had been retained, fortunately, and Firth provides a detailed description of the types of stitching and fabric construction which demonstrates the importance of retaining historic material where possible for future study. With the availability of replica lozenge fabric from a previous collaboration between various museums, a new covering could be carried out using Firth's knowledge gathered from studying the original fabric.

Firth's inspection of the fabric was complimented by analysis to evaluate the originality of paint layers on the original material. Procter, McGeehan and Hallam undertook analysis of paint samples taken from the original fabric of the Pfalz and Albatros treated at AWM and compared this with samples from a Pfalz and Albatros with known provenance from the NASM collection, and which the NASM curator believed to be original (Procter, McGeehan and Hallam, 2000). Paint from a French Voisin Bomber at the NASM was also studied. Paint samples

were mounted in epoxy resin blocks, which were then polished to prepare them for Optical microscopy and UV microscopy to identify paint layers, and SEM-EDXA was also carried out to perform elemental analysis of the paint layers.

The aim of the study was to identify original paint layers and their composition, defining original paint as 'paint applied prior to or during WWI and whose composition is similar to British specifications of the same era' (bearing in mind the Pfalz and Albatros were German aircraft). Procter et al thus assume that 'original' paints are defined as ones containing large quantities of sulphur, barium or zinc, which they argue were common in paint fillers around the time these aircraft were made and are specified in the British standards.

The presence of other elements in paints, most notably titanium, was considered to indicate the use of a later paint since, although available during WWI, it was a very expensive commodity at that time. As such they suggest its presence in large quantities may imply a non-original paint, whilst small quantities may be more indicative of originality. The study defined four potential groups of paints which were found on the aircraft samples. These included:

- Those thought to be potentially original as defined by the study, containing sulphur, barium and zinc.
- Silicon based paints in which Silicon forms the major component, with various additives, e.g. calcium, iron and aluminium mixed in.
- Lead based paints to which some calcium and possibly silica, barium and iron containing compounds were also added.
- A miscellaneous group containing organic elements and a large calcium content with various minor additives. This paint was of a brown colour.

The study does acknowledge that the limited analytical techniques available meant that further information of use could not be gathered. X-Ray diffraction, Procter et al. argue could have provided more detail about the type of titanium dioxide used, which is commonly used in two polymorphs, anatase and rutile. Anatase was first produced for pigment use around 1918, whilst rutile was not made commercially viable as a pigment until the late 1930's, enabling potential post or ante quem dates where the two forms can be distinguished (Conservation and Art Materials Encyclopedia, 2018).

A final issue that arises from this study are potential problems in understanding the historical context and construction of the materials under study. Procter et al. question the potential provenance and originality of certain NASM samples, since they found the fabric to be dyed and no references to this within the historical literature studied. This may reflect an over reliance on British standards, however, when studying German WWI

aircraft which used the special 'lozenge' fabric, which sources describe as being pre-dyed ahead of use (Mikesh 1997, 87). A review of German historical sources would therefore be needed to truly evaluate the historical context of the material and provide judgements as to its authenticity or originality.

Croker and Kemister discuss the practical process of the re-covering project and how the wings of the Pfalz XII and Albatros were re-skinned using two pieces of lozenge fabric, one to cover the upper surface and one the lower (Croker and Kemister, 2009). These were stitched together at the trailing and leading edge of the wing, before being secured to the ribs. They also mention smaller details, such as the use of temporary staples to fix fabric in place before stitching which are small details but important, since such actions would leave permanent traces that could confuse future study.

Croker and Kemister also provide details of the materials used in the treatment. Evasol (an ethylene vinyl acetate co-polymer) adhesive was selected for repairs to internal wooden structural elements and for adhering fabric joins at the wing edges before stitching. This adhesive was used as they argued it was pH neutral and would provide the best options for re-treatment in future. They also applied five coats of Phoenix Cellulose Nitrate aircraft tautening dope to finish the fabric leaving two days between each coat. Croker and Kemister also discuss how potentially original material was found in isolated areas, and that these materials were not treated but left as found.

The project to recover these two aircraft as described by Firth, Procter et al., and Croker and Kemister, demonstrates that full restorations, in which previous skins are removed and replaced, can still be thought through using conservation ethics as these papers attempt to justify the thinking behind the treatments of the Albatross and Pfalz at AWM. It should be noted, however, that they do not acknowledge what is lost through it, namely evidence and information about 1960's and 1970's restoration techniques of historic aircraft, a topic which may not seem of much interest and importance at present but which has still had a profound impact upon how these aircraft are now understood and viewed within the museum, and may be a subject of future study in itself.

Pickman provides a blog account of his approach to managing several deteriorated pieces of doped-fabric separated from the frame of an aircraft several years previously at NASM (Pickman, 2013). The doped fabric was received as rolled up scrolls, with signs of tearing, delaminating surfaces and deformations which Pickman treated using methods adapted from paintings conservation. Pickmans' first action was to relax the material by placing it in an atmosphere of solvents which relaxed the dope, and then adhered it to a fabric backing of Ceconite using Beva 371, a common adhesive used in paintings lining treatments. The Ceconite supporting fabric

was then attached to wooden strainers, enabling a desired tension to be exerted on the material. This was done so that the doped-fabric would remain flattened, enabling visual examination of the imagery and markings on them without having to risk damaging the panels by unrolling them.

Pickman attributes the rolled nature of the doped-fabric panels to the way in which they had been stored rolled up, arguing that this has created a 'memory' in the material causing it to roll up automatically, and thus seems to be relying upon his training and knowledge of similar, related materials to make judgements about how doped-fabric behaves. Work preparing doped-fabric panels as part of this project, discussed further in Chapter 8 on the effects of doping however, suggests that doped-fabric panels may inherently roll up on themselves once no longer restrained. Pickman's treatment, therefore, although enabling easier and safer inspection of the panels, may be impacting one of the most fundamental properties of the doped-fabric, namely the compressive force of the dope-film within the material which may also lead to the material curling up on itself.

This indicates that there is a gap in understanding about the properties and characteristics of doped-fabric by conservation professionals, which may mean that despite best intentions the full impact and consequences of treatments cannot be adequately evaluated. Conservators, therefore, whilst very good at often evaluating how their treatment may seem to benefit an object, may at the same time not fully understand or appreciate what features are lost or risked through it.

4.5.3. The Tautening Properties of Dope

The concern about the continued shrinking of butyrate dopes, and the damage it could be causing to both the external skin and internal structure needs greater exploration as there appears to be some confusion regarding it in the conservation literature. Pearce discusses the issues caused by the continued shrinkage of the Cellulose butyrate dope and the damage to the Albatros D.Va at NWM in more detail, and claims that the 'physical and anecdotal evidence indicates that in many circumstances the contraction does not ever totally cease' (Pearce 2004, 4).

Pearce also makes the more wide-ranging claim that the issue is a widely recognised problem in aircraft management. 'In recent discussions with a number of museums and aviation enthusiasts as widespread as Europe, America and Canada, numerous instances have been reported of aircraft with distorted fuselages, warped wings, torn stitching, wing ribs puncturing the fabric surface, all due to the continual tensioning of the butyrate doped fabric' (Pearce 2004, 4).

Mikesh (1997, 86) also raises concern about the long-term shrinking properties of cellulose butyrate dope after a treatment was carried out on a PA-12 Super Cruiser *City of Washington*. In this case a doped-fabric panel separated from the aircraft after restoration was re-adhered onto another support fabric panel which had been doped. After several years this repair failed, and Mikesh argues that this was due to the continued shrinkage of the cellulose butyrate dope of the support which eventually led to failure of the bond between the doped-fabric panels and caused tearing of the original.

Neither Pearce nor Mikesh provide any evidence or theories as to how or why this continuous contraction may be occurring with butyrate dopes. They do not attribute the same problem of long-term shrinkage to nitrate dopes, however, with contraction thought to cease after several weeks drying.

The observations of Pearce regarding continued contraction of doped-fabric treated with butyrate dope appear to have begun to enter wider conservation knowledge and thinking but with some confusion and misinterpretation. The blog post by Pickman cites ‘Pierce [sic]’ (presumably meaning Pearce), regarding the claim that dopes continue shrinking continuously (Pickman, 2013). It is worth noting here that Pickman does not differentiate between dope types, and that no distinction is made between butyrate dopes, which Pearce recognised as problematic, and nitrate dopes, which he does not.

This concept of the continuous shrinking dope is then further picked up by Maksel who quotes Pickman as saying, “Cellulose nitrate, or dope, is used as a tautening agent, and it’s what allows the fabric to be drum-tight on the surface of an airplane’s frame (Maksel 2018, ¶12). Unfortunately, it continues to tighten over time, and will literally tear itself apart.”

Pearce’s observations regarding the shrinkage of butyrate dope has morphed into a problem with nitrate dope and is stated as established fact, with only empirical evidence to support it, and no investigation as to how, why or whether this process even occurs. These inaccuracies in referencing also suggest confusion and uncertainty within conservation circles as to what dope actually is, how it is made and the difference between the various types.

4.5.4. Environmental Conditions for Displaying Aircraft

Of final interest regarding conservation literature of doped-fabric aircraft is the issue of environmental influences on the material. As has previously been discussed in Chapter 2.3.3, doped-fabric manufacturers were interested in how their materials respond to environmental exposure and Padfield used the information from this work on doped-fabric in the aviation industry in an early work on preventive conservation, using it to

suggest suitable environmental conditions and potential agents of deterioration in museum environments (Padfield, 1969).

Since Padfield's initial use of this information, however, there does not appear to have been much published on the effect of display or storage environment on the condition of doped-fabric aircraft. Mikesch (1997, 63) notes regarding the Domenjoz Bleriot XI that the nature of fabric aircraft may contribute to deterioration of internal structures as 'the fabric not only drew moisture but also trapped humidity within the structure', though this is just a general observation with no other evidence or studies found to support it.

Palermo raises potential climatic issues in the care of the 1905 Wright Flyer III (Palermo, 2000). He notes that during early years of display between the 1950's to 1980's the aircraft benefited from the conditions he identifies as generally good, if unintended, environmental conditions. It was kept largely in darkness due to seasonal, low visitor numbers and a low heating system during winter prevented very low RH conditions which he argued could contribute to drying out of the wooden frame.

Some problems were still observed with the Wright Flyer III, such as mould growth in the fabric and rusting of the wiring, however, which were attributed to problems of extended periods of high RH and so a major project was undertaken during the 1980's and 1990's to improve the climatic conditions. This included improving the fabric of the building in which the plane was housed, which was leaking and had guttering problems, installing de-humidifiers for use during summer months and UV filters on windows. During the late 1990's a Heating, Ventilation and Air-Conditioning (HVAC) system was also installed to provide air conditioning in the building.

The above steps were taken, yet at no time is it made clear what end-state Palermo and his team were seeking in terms of climatic control, or whether the steps were taken for object benefit or visitor comfort. This represents a further problem in the conservation of doped-fabric aircraft in that not only is there a gap in knowledge about the nature of materials by conservators, but that this limits the conservation professions ability to specify appropriate display or storage conditions. Steps such as blocking UV, for example, would be considered generally sensible in museum exhibition spaces, but it is not known if more specific display standards, such as a specific RH range or type of lighting are required.

4.6. Summary

The preceding discussion has demonstrated that the conservation profession has developed standards and ethics by which conservation procedures and interventions should be judged. These standards and ethics, however, do not provide hard and fast rules as to what action is or is not acceptable, but rather guide and

inform the work of conservators. Different working contexts can alter their interpretation, and different individuals or groups may also interpret such concepts in a variety of ways.

When dealing with large, industrial heritage, however, there has perhaps been a tendency to believe that somehow a different set of heritage and management rules apply in which more ambitious restorations and a greater re-interpretation of objects are acceptable compared to other types of heritage objects. This has perhaps been due to the involvement of different groups in such conservation projects, such as volunteers who previously worked with the heritage or hobbyist enthusiasts. Such approaches seems to have been generally adopted when managing collections of doped-fabric aircraft, though this has been increasingly challenged by voices within the museum and conservation profession.

The conservation of aviation collections within a museum conservation context, and within this the more specific issue of doped-fabric aircraft, has therefore been emerging as a field, yet has received very limited attention within published sources. As such the information available to conservators about this material is somewhat confused and at times contradictory. Much of the information available, moreover, such as about the shrinking of dopes, is based on anecdotal experience, demonstrating that a great deal more research and study into the deterioration and conservation of such objects is required.

5. Literature Related to Conservation of Doped-Fabric Aircraft

The section on conservation of doped-fabric aircraft indicates that this is an area of conservation which has not received significant coverage in the literature or resources in terms of conservation research, and there are few published instances of research investigating the tearing in doped-fabric aircraft from a conservation perspective.

There are, however, several related fields in conservation that have received mention within the fore-going discussion, such as paintings conservation, where greater attention has been paid and whose knowledge and practice may be of use in the conservation of doped-fabric. A review of these fields, as well as a discussion of techniques used in measuring strain in museum contexts will be given since, although such studies were not conducted with the conservation of doped-fabric aircraft specifically in mind, similarities in terms of materials, construction and objective make them of relevance to this project.

5.1. Paintings Conservation

This section of the literature review will discuss theory and practice in canvas paintings conservation. Canvas paintings are in certain respects comparable to a doped-fabric aircraft construction, in that they frequently consist of a linen or cotton substrate held under tension, usually by stretching around a wooden frame with a stretcher bar to control the tension, onto which various surface coatings are then applied. These coatings vary, but may constitute an initial size layer, such as rabbit skin or hide glue, followed by a ground layer, and then various layers of paint.

As has already been discussed in this thesis, conservators have investigated and in some instances applied paintings conservation methods, principally lining techniques, for the preservation of doped-fabric aircraft (Chapter 4.4). Some understanding as to how and why these techniques have been considered appropriate, as well as problematic, within a painting conservation context may provide further background as to the conservation challenges faced in applying such techniques in regards doped-fabric aircraft.

Lining describes a range of techniques and processes in which a support layer is applied to the back of a canvas painting, and this support layer may be another piece of fabric or a layer of wax or other polymer. The aim is that the backing should be stiffer than the material being conserved, which means it then bears the tensile loads acting on the material, and if effective prevent damage to the lined canvas. Lining was used to repair, stabilise and prevent various types of damage, such as cracks in the paint layers, delaminating paint and sagging due to a loss in tension. A standard technique in paintings conservation for many years, the process of lining received

increased scrutiny and criticism during the latter 20th Century, as its potential limitations and disadvantages became more widely recognised (Hackney, 2004).

One material for attaching the support lining to the canvas already seen in some of the treatments of doped-fabric aircraft, is an adhesive known as Beva 371 (Berger, 1975). Beva 371 can be heat activated to adhere a fabric backing onto the historic substrate and was developed so as not to react to fluctuations in Relative Humidity, to provide a good bond between canvas and lining, whilst avoiding problems of over impregnation of the original canvas which may lead to further problems, such as staining and irreversibility.

The lining technique had been used for a great many years for preserving canvas paintings, despite there being relatively little understanding as to the causes and mechanical properties of how canvas paintings were behaving. Paintings conservators, therefore, were concerned as to how load was distributed between the different components of a painting, how this might lead to damage and what effect application of a lining might have on the system.

In studies by Mecklenburg originally conducted during the 1980's, the behaviour of different layers of a canvas painting were studied to understand how they behave in isolation under different climatic conditions (Mecklenburg, 2004, 2007). This testing involved restraining a sample at constant extension whilst measuring the force acting on it, and then altering the environmental variable of interest.

Mecklenburg identified hide glue, a typical size for painting canvases, to be the stiffest and strongest component at low RH and therefore concluded that it was this part of the painting, and not the canvas, which supported the tensile stresses acting on the painting under low RH conditions. As RH was increased, however, the load acting on the hide skin decreased until it sustained virtually no load by 80% RH. Mecklenburg therefore argued that under high RH conditions the hide glue would no longer be stiff and could not play a structural role in supporting the painting.

Samples of linen canvas, in contrast, were shown in the region of 20-75% RH to sustain relatively little force compared to the hide sizing. Above approximately 75% RH, however, a significant increase in the force borne by the canvas was measured, which was attributed to swelling of the fibres due to uptake of moisture. Select paint films were also analysed as part of the study, but were found to bear relatively little load compared to either the hide glue and linen canvas.

Mecklenburg related these results to damage observed in canvas paintings by mocking up a canvas painting and exposing it to RH cycles from 90% to 35%, and then back to 90%. Over these cycles cracking was observed at the corners of the painting, which were attributed to the contraction of the hide glue towards the centre of the

painting during low RH cycles. This eventually sufficiently distorted the ground and paint layers as to cause failure, and this was most likely to occur at the corners where the painting is most restrained.

Hedley further investigated the predicted effects of RH made by Mecklenburg using samples of naturally aged canvas paintings taken from the Tate Gallery (Hedley, 1988). These were held under uniaxial tension at constant extension whilst the RH environment was cycled and the load on the samples measured. These experiments were conducted to test whether historic painting samples would behave as Mecklenburg predicted from work on the individual behaviour of each isolated layer.

Hedley's results corresponded well, with the samples experiencing high load at low RH, attributed to the stiffness of the sizing, which gradually decreased with increasing RH. At around 80% RH for most samples the load was found to increase significantly, and was attributed to yarn shrinkage as proposed by Mecklenburg.

Berger and Russell also carried out testing on historic oil painted canvas samples, but using bi-axial testing to test load response to environmental fluctuations (Berger and Russell, 1988). In this experiment they noticed that not only RH, but temperature was also a potential environmental factor of significance due to thermal expansion and contraction when heavy paint layers were present. A rise in temperature, they demonstrated, resulted in paint layers expanding in a restrained space, resulting in either an upward expansion of the paint out of the plane of the painting or plastic deformation of the paint material if restrained. When temperature then decreased, contraction would occur leading to the reverse and, over several cycles, this would lead to cracking of the paint including potential cupping and blistering.

These experiments also demonstrated the problem of creep in a canvas substrate. When a primed canvas was initially tensioned, Berger and Russell found the load would invariably decrease until it reached what they termed it's 'maximum sustainable tension', values of which varied depending upon the type of canvas and starting load. Similar to Hedley and Meklenberg's results, moreover, Berger and Russell observed a significant increase in tension at high RH, which was again attributed to shrinkage of the canvas on swelling. When RH was then lowered, a reduction in tension of the canvas was measured which was suggested to be due to small plastic deformations in the weave as the restrained yarns could not contract.

In canvas paintings with a heavy paint layer, the paint layer was also believed to have an effect during cycling RH, expanding at high RH. There was therefore a contraction of the canvas simultaneous to an expansion of the paint layer. This expansion of the paint layer thus reduced the measured tension expected due to the contracting canvas. The research thus supported the conclusion that it was not the canvas on its own

responsible for defects forming in painted surfaces, but that it is the interaction of the various layers, and their relative stiffness and response to environmental fluctuations which plays the bigger role.

These results, Berger and Russell argued, showed the benefit of using a lining support if controlled environmental conditions could not be maintained. The lining, they argued, provided it were sufficiently stiff and properly applied, would be resistant to creep and prevent the expansion and contraction of the paint layer, and hence limit expansion induced cracking. If a canvas were not lined then they argued the painting must be kept in closely controlled RH and temperature environments to prevent the shifts in stress between the various layers of the structure.

Bi-axial loading experiments have also been conducted to examine the effect of applying lining layers to paintings and the response of these various structural elements to changes in RH. In one set of experiments, Young and Ackroyd describe the results of applying a variety of lining techniques (hot wax, Beva 371 and proteinaceous glue) to the backs of paintings and lining canvases held under tension (Young and Ackroyd, 2001). These experiments are of interest as providing a potential comparison to the application of dope to aircraft fabrics.

Application of the wax and glue to the lining materials appears to have generally resulted in an initial drop then rise in tension of the sample. The decrease in tension is attributed to lubrication of the weave caused by the mobile wax enabling re-alignment of the structure at contact points between warp and weft. The rise in tension is then a result of contraction of the lining material, as well as locking of the weave which prevented further expansion due to creep.

Examination of the lined materials response to RH was also conducted. This established that below approximately 65%RH, an increase in RH resulted in a rapid loss of tension for proteinaceous glue lined samples attributed to the response of the size. Whilst there was also a decrease in tension for hot wax and Beva 371 lined samples, these could not be distinguished from potential creep effect from the initial tensioning. Only the Beva 371 demonstrated significant increases in tension attributed to canvas shrinkage once the RH level went above 55% which was attributed to the fact Beva 371 adheres only to the outer surface of the canvas, which was therefore still able to absorb moisture. In hot wax and glue lining, in contrast, full impregnation of the canvas was achieved, which prevented moisture absorption and the subsequent contraction.

A further technique of paintings conservation besides lining which may be of interest is known as thread-to-thread repair (Demuth *et al.*, 2011). In this process, tears in a painting are repaired by individually re-entangling

the ends of the yarns and adhering these back together. This technique can result in near invisible repairs, and is probably one of the best techniques for visually hiding the tear as if it had never happened.

The technique does pose practical difficulties, however, in that it is a very time-consuming process, requires unravelling of the yarn ends which may be difficult once impregnated with dope, and is usually undertaken with paintings that can be easily moved for ease of working access.

What may be of interest in the technique, however, is a system known as a 'trekker'. There are various designs and methods by which a trekker works, but the essential concept is a system that can bring the edges of a tear back together whilst the thread-to-thread repair is conducted. There are commercially available trekkers, which require a wooden frame as usually found on a canvas stretcher to operate, but it is also possible to develop in house solutions for specific problems. The realignment of tear edges is one problem which has been identified when treating doped-fabric aircraft, and so consideration as to how such trekker systems might be adapted for use in aircraft conservation may be of value.

A review of the literature in paintings conservation therefore suggests that a major concern in many canvas structures is understanding the effect of RH on the structures stiffness and tension. It also indicates that understanding the properties of individual components in the structure, as well as investigating the system as a whole can be beneficial.

Finally, it is worth noting that whilst paintings methods may be of immense interest to conservation of doped-fabric aircraft, it is important to be aware that there are concerns about its application to canvas paintings and there is still a great deal more to be understood regarding how lining systems behave. Applying lining to a related but different material, namely doped-fabric, about which much less conservation research has been undertaken compared to canvas paintings, requires care.

Many of the above studies have relied upon tensile loading experiments which have either required samples to be removed from historic materials (mostly paintings which were considered of little value) or modern materials to be mocked up to replicate historic canvases. This may limit the range of experiments possible since studies of paintings, and indeed most heritage objects, tend to have restrictions in the size and number of samples that can be removed and methods of testing which result in unacceptable changes to an object are not permissible.

5.2. Plastics and Textile Deterioration

The conservation of plastics and textiles has received significant attention within the conservation literature. Textiles have long been of interest as they occur in numerous heritage artefacts, including clothes, flags, burial shrouds and tapestries. Although a much more recent type of material, plastics have also received attention due to the growing number of objects within museum collections made from this material, and there has been growing recognition that the conservation of plastics represents a major challenge for institutions with such collections (Blank, 1990; Mossman, 1991; Scott Williams, 1991; Shashoua, 2008). A review of how they have been studied in conservation literature will be of use for indicating the types of issues and problems that may be expected of a doped-fabric made of a textile and semi-synthetic plastic composite.

One of the first tasks of conservation research into these material types has frequently been identification, as basic information detailing what objects are made from is often lacking. There are a large number of techniques for materials characterisation to choose from, but Fourier Transform Infra-red (FTIR) and Raman techniques have proven especially popular in the conservation analysis of plastics and textiles, and have been used to distinguish between various cellulose derivatives and cellulosic fabrics (Shearer and Doyal, 1991; Groom, 1999; Garside and Wyeth, 2003, 2006; Paris and Coupry, 2005; Meincke *et al.*, 2007; Asquier, Colomban and Milande, 2009; Chércoles Asensio *et al.*, 2009; Nel, Lau and Baybrook, 2011). Other techniques used for identification by conservators have included various other types of molecular spectroscopy and mass spectrometry and more basic, sometimes less reliable tests, such as burn tests and spot testing with chemical reagents (Coxon, 1991; Ormsby, 2005; Stuart, 2007).

Although effective at identifying certain compounds, FTIR and Raman spectroscopy often cannot fully characterise an objects composition and so other techniques have been used in conservation studies. Two other common techniques include X-Ray Diffraction (XRD) and X-Ray Fluorescence (XRF). These have been used to aid in the identification of additives, such as pigments, corrosion products, or the elemental composition of alloys (Dupont and Tétreault, 2000; Parras-Guijarro *et al.*, 2006; Meincke *et al.*, 2007; Tsang *et al.*, 2009; Mulholland *et al.*, 2017). In many of these identification studies a combination of complimentary techniques is required to characterise a material as fully as possible.

The analytical techniques above amongst others have been used not only for identification, but are also used when investigating the deterioration of objects made from cellulosic fibres and cellulose derivatives, attempting to understand how and why these materials change, and hence identify at risk objects and halt unwanted degradation (Edwards and Falk, 1997; Bellot-Gurlet, Pages-Camagne and Claude, 2006; Schilling *et al.*, 2010;

Littlejohn *et al.*, 2013). Although in some respects very different materials, certain similar processes have been identified in the deterioration of both cellulosic textiles and cellulose derivatives.

In high RH conditions, the process of acid hydrolysis has been identified as a potential deterioration mechanism leading to break down of such materials (Hon, 1994; Timar-Balazsy and Eastop, 1998; Daniels, 1999; Dupont and Tétreault, 2000; Tétreault *et al.*, 2013). This is due to the formation of acidic compounds when water molecules react with Volatile Organic Compounds (VOC's), which then preferentially react at the carbon atoms around the glycosidic link (Florian, Kronkright and Norton, 1990). This leads to breakages of the glycosidic bonds forming the cellulosic back bone, decreasing the molecular weight of the cellulose polymer chains and has been linked to drops in tensile strength and embrittlement.

The source of VOC's may vary, and could originate from an external source, such as pollutants, or be inherent to the objects. Acid hydrolysis can be especially problematic in cellulose nitrates and cellulose acetates as these materials may release nitryl or acetyl groups respectively, which in moisture form acetic and nitric acid. Acid hydrolysis may also become auto-catalytic and almost impossible to stop even by limiting moisture in the environment or removing the original source of VOC's as the break-down of the cellulose backbone releases further free radicals able to continue the reaction cycle.

The manner in which materials were manufactured may also result in inherent instability (Quye, 2014). The use of sulphuric acid as a catalyst when manufacturing cellulosic plastics or the introduction of certain additives, such as camphor and triphenyl phosphate plasticisers, may also speed up deterioration rates of such materials (Reilly, 1991; Quye *et al.*, 2011). Sulphuric acid, for example, if not fully removed during manufacturing by thorough washing, has been found to form hygroscopic sulphate ester forms of cellulose which further promote acid hydrolysis.

Storage conditions are also recognised to be potentially influential in determining the deterioration rates of cellulosic objects undergoing acid hydrolysis. Objects stored in closed conditions are particularly susceptible to chemical degradation as the decomposition products are trapped within the object, and so react further to cause additional, secondary decomposition reactions. This process has been identified as a particular challenge in film archives due to storage of nitrate films in metal tins, and the potential increased flammability of such materials as deterioration processes progress (Health and Safety Executive, 20014; Heckman, 2010).

The problem of sealed storage could be of relevance to doped-fabric aircraft since, although they are generally kept in very open conditions on display in gallery, the enclosed, interior surfaces of the wings could have limited air exchange and so undergo a very different deterioration process compared to the exterior surface.

Ultra Violet (UV) radiation is also believed to affect the chemical structure of cellulosic materials (Hon and Gui, 1986; Moniruzzaman, Bellerby and Mai, 2011; Berthumeyrie *et al.*, 2014; Bussiere, Gardette and Therias, 2014). Far UV radiation, $\lambda < c.340\text{nm}$, unlikely to be found in a museum environment, has been found to directly break the chemical bonds in the backbone of a cellulosic chain (Kolar *et al.*, 2000), whilst the acetyl and nitril side groups, in contrast, may be liberated by longer wave-length radiation in the near UV and visible light region. These side groups once liberated may undergo secondary reactions resulting in compounds that may further react with the object and cause or speed up deterioration reactions and chain scission as discussed above.

The presence of additives and impurities may have a role in determining the extent and rate of photo-induced chemical degradation. Impurities may interact with wavelengths of light which pure cellulose would not, thus absorbing energy at wavelengths not normally associated with cellulose deterioration (Kolar *et al.*, 2000). In the case of linen and cotton fabrics, although these are both primarily formed of cellulose, they potentially also contain different amounts and types of impurities, such as lignin and hemicellulose (Akin, 2013). Linen tends to contain a higher concentration of such impurities than cotton due to the processes which separate the linen fibres from the other components forming the stem, and these impurities are may play a role in making linen more prone to degradation than cotton. As previously discussed, the composition of a cellulosic fabric is highly dependent upon its manufacturing history, and so predictions as to how historic materials may behave is not straightforward (Chapter 2.2.1).

Thermal degradation appears to play little role directly in the deterioration of museum objects made from cellulose nitrate, at least under normal gallery conditions (Selwitz, 1988). At temperatures below approximately 90°C, the rate of thermal deterioration appears to be relatively slow compared to other deterioration processes and is primarily related to the inherent stability of the material itself. The effect of temperature is therefore primarily due to its influence on the rate of these reactions attributable to other deterioration mechanisms. Cold storage down to approximately -20°C is one option recommended for certain plastics collections and film archives to help reduce reaction rates (Shashoua, 2014), though would be impractical in the case of doped-fabric aircraft.

Selwitz emphasises that very different forms of cellulose nitrate may occur by manipulating specific polymer properties, such as the degree of crystallinity, the degree of substitution and distribution of nitrate groups along the cellulose backbone, the average molecular weight and method of manufacture (Selwitz, 1988). Highly nitrated products, for example, which contain a large proportion of tri-nitrated rings, are highly unstable and used for explosives. Di- or mono- nitrated versions in contrast are much more stable and so may be used as binders in products such as inks and paints as well as for moulding objects. These same polymer properties also

influence the behaviour of cellulose acetates, which have different properties depending upon the specific chemical characteristics of the material being studied (Heinze and Liebert, 2004).

It therefore seems probable that deterioration of doped-fabric leading to tearing may in part be attributable to the general processes as described above, but will be unique in each case as the result of a complex inter-play of many variables related to the manufacture, history and current storage of each individual object. It is also noteworthy how similar the concerns of conservation studies are regarding the issues of acid content and light exposure to those of historic research concerned with maximising aircraft fabric life discussed in the historic literature in chapter 2.2.

One potential treatment option for managing the aging process in historic cellulosic objects involves washing of artefacts in a pH neutral or mildly alkaline solution to try and neutralise and remove acidic compounds (Block, 1982; Tse, 2001; Seery, 2013; Steczek, 2015). Such approaches have been used and investigated in paper and textile conservation, though their potential use in plastics is less documented or researched and could risk the removal of water soluble components. Another approach developed has been that of grafting cellulose polymers with acrylic monomers (Princi *et al.*, 2005, 2007), though there do not appear to be many examples of this approach being adopted, possibly due to issues with re-treatability and the method for application to a historic material.

It ought to be emphasised, moreover, that the exact relationship of different deterioration agents is not always precisely understood as the effect of different mechanisms are often studied in isolation and so does not account for the complexity that occurs when multiple variables interact may (Feller, 1994). To replicate deterioration process, moreover, modern surrogates may be artificially aged by increasing exposure intensity to the variable of interest. Such increased exposures, however, may result in alternative deterioration mechanisms than those which occur at lower intensity over many years and materials which do not accurately reflect the properties of historic material (Micheal, Tera and Othman, 2005).

The isolation of deterioration factors, moreover, may influence results. The presence of oxygen, for example, whilst potentially a cause of deterioration reactions due to oxidation, may initially reduce the apparent rate of deterioration under UV exposure, as it has been suggested it promotes cross linkages in cellulose nitrate (Hon and Gui, 1986). A similar problem may also occur when photo-aging materials as to whether cycles of lightness and darkness are used, or continuous exposure. Under cycling light conditions, periods of darkness may enable reactions that would not occur under constant exposure (Thei, 2011).

Finally, as highlighted in chapter 4.1, making decisions based on studies of materials deterioration ultimately rest on subjective decisions as to what is a negative outcome. There are a number of metrics to demonstrate deterioration which range from potentially invisible alterations, such as a change in pH, tensile strength or the release of certain chemical compounds, through to visible alterations to the material, such as colour changes and cracking. Using these measures as signs of deterioration, however, does not necessarily entail that these changes would be problematic in a real-world situation, and so there is a layer of interpretation necessary between the results of a scientific investigation and applying these to determining how a collection ought to be managed.

5.3. Strain Monitoring applied to Failure and the Heritage Context

A key purpose of measuring strain within historic objects is to understand what causes the historic material to deform and whether there are critical parameters at which it may fail, i.e. crack or tear. Investigations of strain in organic materials have linked fluctuations of RH to fatigue failure of historic materials and, through study of how materials respond to changes in RH have attempted to provide environmental guidelines within which failure, or at least the risk of it, may be reduced (Michalski, 2011; Kupczak *et al.*, 2018). There has consequently been debate as to what form appropriate RH boundaries should take, and how far such recommendations might be generalised across different materials and contexts within a display environment (Michalski, 2007; David and Mecklenburg, 2011).

Within this context, techniques for strain monitoring such as Digital Image Correlation (DIC) and Speckle Pattern Interferometry (SPI), have often been used for the study of art works as they are non-invasive and do not require direct, physical contact with the object under study (Young, 1999; Dulieu-Barton *et al.*, 2005; Tornari, 2007; Miles *et al.*, 2008; Malesa *et al.*, 2011; Lennard and Dulieu-Barton, 2014). DIC and SPI have a further advantage in that they monitor strain across an area, enabling a strain map of an entire surface to be produced.

Other non-invasive options for measuring strain which have been applied in heritage contexts include laser measuring systems, for example a laser sensor at Hampton Court Palace was used to measure the displacement of the bottom edge of a hanging tapestry from the floor, whilst the Mary Rose Trust employed a Total Station Theodolite (TST) surveying technique to map the deformation of the ship over time whilst drying out (Colson, 2017; Frame *et al.*, 2018). Such techniques provide very accurate measurements of the object relative to a fixed point, and did prove effective for these projects. The Hampton Court monitoring system, for example, demonstrated a link between the deformations of the tapestry and RH fluctuations, and based on this work has

been undertaken to further develop a monitoring system to measure strain at multiple locations across the tapestry (Vlaschou Pers. Comm 2017).

Techniques such as DIC and SPI, however, are very sensitive to vibrations or other disturbances in their environment which can make even laboratory work in relatively well controlled conditions challenging, and long-term in-situ gallery work all but impossible. Setting up for DIC, SPI and TST, moreover, requires sufficient space to assemble the equipment with optics focused on the area to be studied, which would be challenging with the limited resources, space and location of aircraft hanging from the ceiling of *Flight*. Such non-invasive techniques, therefore, would generally not be suitable for *in-situ* application at the Science Museum to directly monitor deformation of the historic aircraft on display.

In order to address monitor the deformation of doped-fabric, therefore, a further option is to use a sensor directly adhered to the material itself. Resistance strain gauges are a common and widespread technique for measuring strain within engineering contexts, but there are relatively few instances of them being used in the conservation profession. Where they have been used within conservation it is predominately in studies of the response of wood panels to changes in RH, demonstrating that wooden objects react almost instantaneously to change in RH, and that a decrease in RH leads to a shrinkage of the panels (Mills and Fore, 2000; Richard, 2007; Ekelund *et al.*, 2017).

The limited use of strain gauges within a heritage context is likely largely due to the need to adhere them to the substrate which is not usually considered suitable for historic materials. They do have the advantages, however, of being relatively insensitive to surrounding conditions and simple to set up, so are potentially suited for use in a gallery setting such as *Flight*. The large size of the aircraft under study in this project, moreover, relative to the size of any potential marks or damage from gauges which may be 1 or 2cm in each direction, is minimal and considered acceptable to the Science Museum conservation staff. This makes RSG's a potentially appropriate tool for making direct measurements of strain *in-situ* on the historic aircraft in *Flight*, enabling monitoring of their response to the climatic conditions found on gallery.

The suitability of strain gauges has also been investigated previously for use on textile and composite textile materials. Research in this area has emphasised the importance of using as large a gauge area as possible relative to the unit size of the weave, as micro variations at scales smaller than the weave can lead to significant variations in strain distribution. Provided larger areas are measured, however, such local variations average out such that a measurement more representative of the textile as a whole may be obtained (Masters, 1996; Masters and Ifju, 1997; Lang and Chou, 1998). It is important, moreover, to bear in mind the limitations of strain

gauges in that they measure only the average strain over the area where the gauge is active, and so may be susceptible to local variations in the strain field making them unsuitable for evaluating the global response of a textile sample.

Beyond use of strain gauges for monitoring response of the doped-fabric to changes in climatic conditions, it may also be possible to use such sensors in the study of deformation of the material during failure by monitoring strain at the crack tip, and the effect of patching by measuring deformations in the material around the patch. The phenomenon of spontaneous tear growth has already been observed occurring on the aircraft in *Flight*, where the opening and further growth of tears has been documented (chapter 3.2.1). This process can be explained using Griffith's calculation for energy in a system with a crack opening:

$$E_{Total} = 2(\gamma_s + \gamma_p)aB + \frac{\sigma^2}{2E}V - \frac{\sigma^2}{2E}B\pi a^2 \quad [6.1]$$

Where E_{Total} is the total energy of the system, γ_s is energy to break atomic bonds per unit surface area, γ_p is the energy from plastic deformation at the crack tip per unit surface area, a is the crack length, B is the depth of the material, E is young's modulus, σ the applied stress and V the volume of the material

The equation is comprised of the energy needed to be put into the system to form the two new surfaces of the crack edges plus the mechanical strain energy to deform molecular bonds in non-cracked areas, less any strain energy released due to the crack opening. Initially, at small values of a , the amount of energy required to form new surfaces will increase faster than the rate at which strain energy is released due to growth of the crack. This means that the crack will be stable at small crack lengths as more energy would need to be introduced into the system to cause growth of the crack.

As the crack length increases, however, it will eventually reach a critical point at which E_{Total} reaches a maximum. Past this point the strain energy released due to growth of the crack will increase much faster than that introduced by the formation of new surfaces. The crack consequently becomes unstable and spontaneously grows since any growth in the crack length, rather than increasing the energy of the system, will cause it to decrease to a more stable state.

A formula for the critical stress at which spontaneous failure of a crack tip occurs can be derived from formula 6.1:

$$\sigma_f = \sqrt{\frac{G_c E}{\pi a}} \quad [6.2]$$

Where σ_f is the stress of failure, E is young's modulus, a is the length of crack, G_c is Griffith's Critical Energy Release Rate and a the crack length

From Equation 6.2 two important features determine when the critical stress is exceeded; the crack length, a , and the Young's modulus of the material, E . An increase in size of the crack length or decrease in the Young's Modulus reduce the critical stress at which a tear is likely to occur and thus make failure more likely. This would indicate that when managing tears in historic material, three main options are available to conservators:

- To reduce the length of the tear already opened
- Decrease the modulus of the material around the crack tip
- Redistribute stress at the crack tip

The process currently used of applying a doped-fabric patch can be seen to be effective at preventing crack growth by effectively reducing the length of the crack to 0 and presumably increasing the stiffness of the area patched by increasing the depth of the material, and hence raises the young's modulus.

As already discussed, however, the concern of such a treatment is that although highly effective at stabilising a tear in that one area, the contraction of the doped-patch may exert new forces in other parts of the historic material and thus lead to failure in other parts of the structure. Since stress cannot be measured directly, however, a method to monitor strain at the crack tip and in the area surrounding a patch (or potential other conservation method) is required to assess its potential effects and, as discussed above, RSG's may be appropriate for this purpose.

RSG's are constructed of a very fine wire grid backed with a thin polymer support film (Potma, 1967; Vaughan, 1975) (Figure 5-1) that are then mounted onto a substrate by adhering the gauge into position, usually with an epoxy or superglue. As the substrate expands and contracts the strain gauge experiences the same strain and this results in a change in the surface area of the fine wire forming the gauge grid. The surface area of the gauge is related to its resistivity, and the length of the gauge and the resistance of the gauge are related by the Gauge Factor (GF), K :

$$k = \frac{\frac{\delta R}{R}}{\frac{\delta l}{l}} = \frac{\frac{\delta R}{R}}{\epsilon} \quad [5.1]$$

Where R = Gauge resistance, δR = change in gauge resistance, l = gauge length, δl = change in gauge length and ϵ = strain

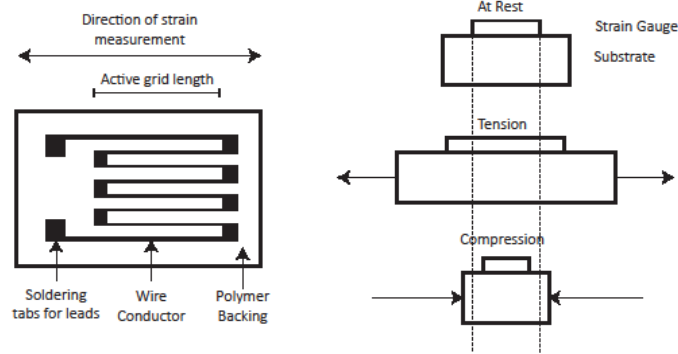


Figure 5-1: Resistance strain gauge design

From equation 5.1 it is seen that one desirable feature of a strain gauge would be a high GF, since this will produce a greater sensitivity of the gauge to smaller changes in strain. Even with a high GF, however, the change in resistivity is usually very small and so the signal must be amplified using a Wheatstone Bridge circuit, in which a change in one of the resistors forming the bridge causes a change in the Voltage (V_{WB}) measured across them (Figure 5-2).

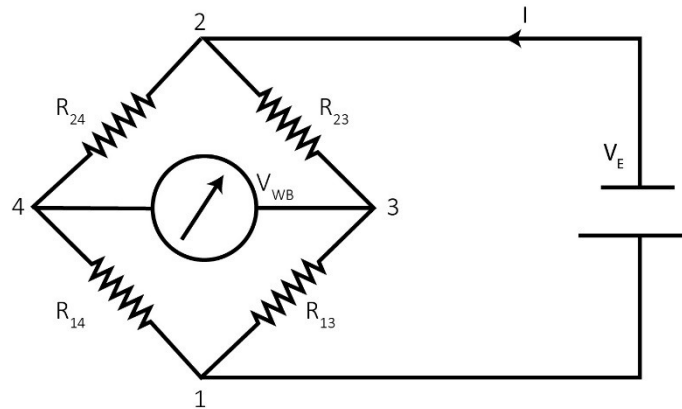


Figure 5-2: The Wheatstone Bridge Circuit

The circuit functions by measuring the voltage across the four linked resistors, one or more of which may be substituted with a strain gauge. Provided the GF (K), excitation voltage (V_E) and voltage across the bridge, V_{WB} are known, then the strain due to a change in resistivity may be calculated:

$$\varepsilon = \frac{4V_{WB}}{KV_E} \quad [5.2]$$

Before application in a gallery setting, however, the practicality of strain gauges for the study of doped-fabric needed assessing in a controlled setting. Doped-fabric panels to simulate the material found on an aircraft were therefore prepared for use in a variety of experiments in which the strain response of the panels was measured using resistance strain gauges (Chapter 6.1).

5.4. Summary

The conservation of materials related to those used in making doped-fabric aircraft has provided some insight into the likely types of mechanical and chemical deterioration taking place. The consideration of paintings deterioration has shown that environmental conditions, particularly RH levels, and the response of restrained canvas structures to such conditions is likely to play an important role in deterioration of such materials. The discussion of paintings conservation techniques, in particular the debate around lining, has demonstrated that even in a field of conservation where a relatively large amount of research has been applied, ideas and approaches as to what constitutes the ‘best’ treatment option remains open to debate.

Similarly, studies into plastics and textile conservation has demonstrated that environmental conditions play an important role in the chemical deterioration of historic objects made of materials also used in doped-fabric aircraft manufacture. Processes leading to chain scission, such as acid hydrolysis, are among the most serious problems, especially for cellulose based plastics, as these can result in a considerable decrease in tensile strength and structural stability.

Studies measuring the dimensional response of museum objects, however, are more limited, and have tended to employ optical, non-invasive techniques which would be of limited use for *in-situ* studies of doped-fabric aircraft on display in *Flight*. Other studies, however, have made use of resistance strain gauges to measure the strain response of wood to fluctuations in RH, and it is suggested strain gauges may also be appropriate for use in the investigation of doped-fabric skins to monitor both the response of fabric to climatic conditions, but also to monitor behaviour at the crack tip and thus the effect of different patching mechanisms.

6. Experimental Methodology

The previous chapters have highlighted a range of issues surrounding the treatment of doped-fabric aircraft at the Science Museum and in the wider conservation profession which need to be addressed. The first is that of material identification and verification, to explore what the Science Museum doped-aircraft are made of. It has been assumed by conservators at the museum that the aircraft are constructed of traditional doped-fabric materials but, given previous interventions and a lack of detail in the technical file records, this cannot be verified through documentation alone.

Analysis is therefore required to determine the materials of construction, for which purpose samples were taken from the technical files of the museum aircraft as well as from certain doped-fabric aircraft on display in *Flight*. Section 6.3 of this chapter provides descriptions of the historic materials available for study and the sampling methodology.

There is then the problem in the use of doped-fabric patching, which has been identified as potentially unsound from a conservation perspective due to the ethical and long-term risks it may cause due to limitations in re-treatability and initiating further failure in other parts of the historic skin. Developing and testing a new treatment is no simple process, however, since first it is necessary to identify what is actually desired of a treatment, and then identify appropriate metrics by which these outcomes may be measured and compared. Rather than attempting to investigate new treatments, therefore, this project aims to develop a methodology by which the effect of doped-fabric patches, in which the potential limitations and problems as already identified may be assessed, and against which alternative treatment approaches might be evaluated.

The investigation of doped-fabric patches requires breaking down into three smaller questions, the first being the effect of doping a fabric. As discussed, there are concerns in the conservation profession that dopes may shrink almost indefinitely, eventually tearing the fabric skin apart or destroying the frame beneath it (Chapter 4.5.3). More information regarding the drying mechanism and the compressive forces exerted by dope films on fabrics is therefore needed to judge its suitability for use in conservation treatments.

As was also raised in the conservation literature review, a potential problem for stretched canvas painted structures and other organic materials are fluctuations in Relative Humidity (RH) levels, which may play a role in failure or distortion of the material (Chapter 5). The historic literature has indicated that doped-fabric is likely to be similarly highly sensitive to RH fluctuations as increases in moisture levels were believed one of the main obstacles in keeping aircraft skins taut. Given the unstable RH conditions occurring in *Flight* (chapter 3.5), further information as to the speed and scale of doped-fabric response to RH fluctuations is required to help

conservators better understand its effects and advocate for more suitable environmental conditions display and storage conditions if required.

Finally, information regarding the patching technique itself and its effect on the tear and surrounding skin was needed. This project therefore sought to investigate the effectiveness of patches in terms of stabilising the tear and limiting further potential growth, as well as its effect on the strain of surrounding material, as this was identified as a fundamental reason, and at the same time limitation, when employing such a conservation approach.

6.1. Laboratory Resistance Strain Gauge Experiments

To study the effect of doping fabric, the impact of RH and the effect of tearing then patching, panels of doped-fabric were created to mimic the construction of doped-fabric aircraft on the gallery and the strain of these panels was measured using strain gauges. This section will describe the process by which these panels were constructed and the strain measured, the RH cycling process and the stages in the experiment used to test the variables of interest.

6.1.1. The Preparation of Fabric Panels

To prepare samples of doped-fabric that could simulate doped-fabric as found on an aircraft it required restraining fabric under tension whilst dope was then applied. To achieve this, acrylic frames were made to restrain the fabric, each frame consisting of two separate sheets of 8mm thick acrylic, which could be screwed together with the fabric clamped between them (Figure 6-1).

The external dimensions of the frames were 290x290mm, the size being limited by the dimensions of the humidity chamber available at the time of fabrication. The central area of each acrylic panel measuring 230x230mm was cut out using a milling machine making this the area of the fabric once mounted in the frame. The two sheets of acrylic used in making each frame were milled simultaneously to ensure alignment where the inner edges meet. Screw holes were then drilled along the edges of the acrylic enabling the two pieces to be tightly clamped together, securing the fabric in place between them. The faces of the acrylic were also covered with masking tape to protect them from the dope solvents.

Type 9F1 Irish Linen from LAS Aerospace was used for making the fabric panels. When mounting fabric into the frames, the warp and weft directions were aligned with the edges of the lower frame part so that the weave was aligned squarely to the frame edges. Another consideration was to consistently load the fabric between panels. For this, the fabric was tensioned over the lower frame with the use of a clamping system around the edges,

which was repeated for each frame. The top fabric panel section was then screwed down over the top to secure the fabric in place.

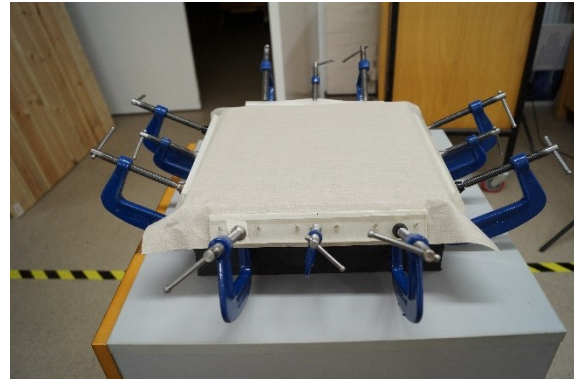
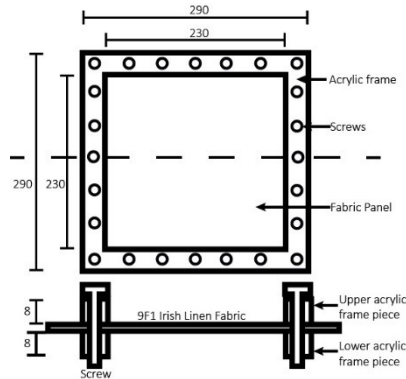


Figure 6-1: Left, Schematic of the acrylic frames used in constructing doped fabric panels (dimensions in mm). Right, a fabric panel being tensioned over the lower part of the frame before the top section could be secured over the top.

Once held within the frame, linear foil strain gauges, type EA-06-250AE-350 (Vishay Micro-measurements), were adhered onto the underside of the fabric (the side not being doped) using MBond200 (cyanoacrylate) superglue. These gauges were used in all experiments and were selected as they have a large grid area compared to the unit size of the weave. Two portable P3 type data loggers were available which enabled a maximum of 8 gauges to be in use at one time using a quarter bridge set up with each gauge.

Two different configurations of strain gauges were used. In configuration 1, two gauges were adhered per panel, enabling up to 4 panels to be monitored at one time but limiting the analysis of strain to only two points per panel (Figure 6-2). A gauge measuring strain in the warp direction was located with its mid-point over the centre axis in the warp direction, with its top edge against the centre axis in the weft direction. A gauge measuring strain in the weft direction was located normal to the warp gauge and directly behind it over the central warp axis, 15mm back from the central weft axis. The four panels set up with this configuration were named Con1A, Con1B, Con1C and Con1D.

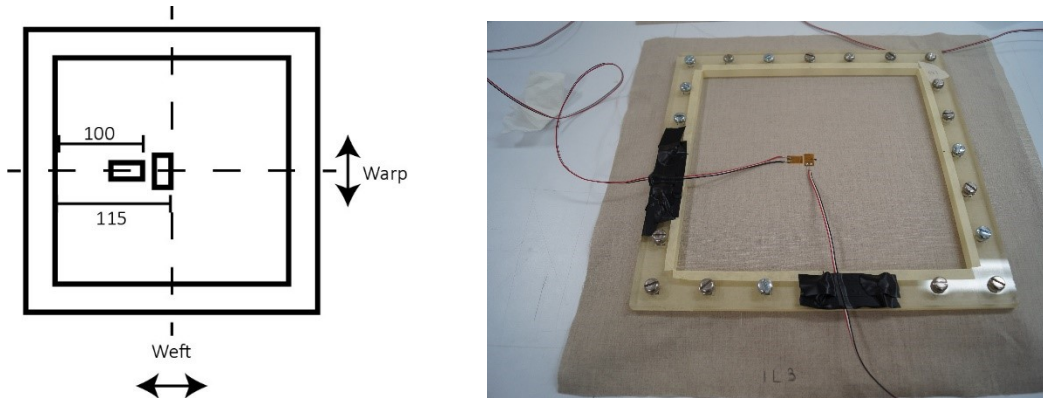


Figure 6-2: Configuration 1 type panels (diagram is not to scale, and values are dimensions in mm)

This gauge configuration was created with the three main purposes in mind:

- to study the response of the fabric panels to changes in RH
- to study the effect of a simulated tear on the panel and strain behaviour at the crack tip
- to preliminarily assess different patching techniques not currently used at the Science Museum

The number of gauges was limited to two so that the number of panels made could be increased in case of variability during the experiment. The location of the warp gauge was chosen at the centre so as to be suitably sited to measure behaviour across the tip of a simulated tear, which was cut during a later stage of the experiment in line with the weft. Details of the RH cycling, tearing and patching process are provided in the next section, 6.1.2.

In Configuration 2, four gauges were attached to one fabric panel as this enabled a more detailed analysis of strain distribution across the panel but had the drawback of limiting the number of panels that could be run simultaneously to two (Figure 6-3). Three gauges were located on the centre axis in the direction of strain to be measured, with the edge of the gauge in position 1 set 5mm away from the centre point. The subsequent gauge positions, 2 and 3, were then set at 32.5mm intervals from gauge 1 towards the edge of the acrylic frame. The strain gauge in position 4 was located normal to the other gauges, midway between positions 1 and 2 but slightly offset to ensure its lead wires would not interfere with the other gauges. Panel Con2_A was set up with gauges 1-3 measuring strain in the warp direction, panel Con2_B with gauges 1-3 in the weft direction.

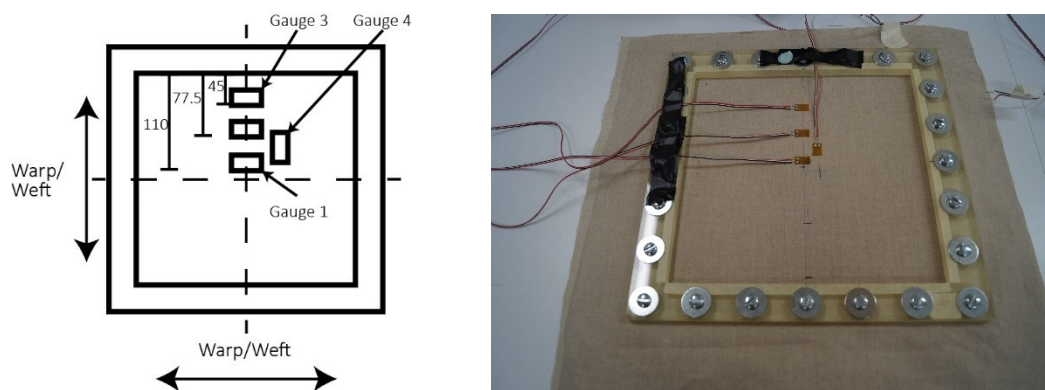


Figure 6-3: Configuration 2 type panels (diagram is not to scale, and values are dimensions in mm)

This configuration was used in experiments focusing on the effect of tear growth and the use of patching as currently used at the Science Museum on strain. The use of the additional gauges compared to configuration 1 enabled the effect of tears and patches over a greater area of the panel to be monitored. The gauges in this configuration were set slightly back from the centre due to the size of the patches used which came right to the centre of the panel. Further details of the RH cycling, tearing and patching process are provided in the next section, 6.1.2.

The identification of individual strain gauges was made according to the following convention:

ConXX_YYYYG

ConXX denotes the strain gauge configuration and panel name

YYYY denotes the direction in which the strain is measured (warp and weft) and G the strain gauge position where multiple gauges in one direction were used, with higher numbers located increasingly further from the centre.

Strain gauge Con2A_Warp2, for example, would refer to the gauge second furthest from the centre of a panel measuring strain in the warp direction. A list of the panels and gauges used as well as the experimental conditions they were exposed to is provided in the next section (Table 6-1, p.138).

6.1.2. Cycling of the Relative Humidity

An RH chamber measuring 800x500x300mm was constructed using polythene sheeting which could hold up to four panels at a time simultaneously, in order that panels could be exposed to the same RH conditions for comparison. The RH of the chamber was controlled using saturated salt solutions; 200ml 50%(w/v) potassium acetate and 200ml 50%(w/v) sodium chloride solution. Sodium chloride saturated salt solutions can maintain an

RH of $75.29\% \pm 0.12$ at 25°C , and was used to create a high RH environment defined as $\text{RH} > 65\%$. Potassium acetate saturated salt solutions can maintain an RH of 22.51 ± 0.32 at 25°C , and was used to set low RH conditions defined as $\text{RH} < 30\%$ (Omega, no date).

These RH conditions were decided upon as representative of the bounds in *Flight* to which the aircraft were routinely exposed on a seasonal basis (Chapter 3.5). The chamber was placed in ambient conditions with no further RH controls in place to manage the rate of change. No controls were set for temperature either, since although temperature and RH are linked, the presence of the saturated salts limits this effect.

Whenever panels were placed into the RH chamber, and before RH cycling could be carried out, the panels were acclimatised to low RH conditions to stabilise the strain measurements. Panels were considered stable once the overall strain change over 1 hour was less than $5\mu\epsilon$ (0.0005%). RH was then cycled by altering between low and high RH conditions by switching the saturated salt solutions. Every cycle began at low RH conditions, with one cycle comprising two steps; step 1 raising the RH to high and step 2 then returning it to low conditions. Each whole cycle typically took 48 hours, with each step occurring over 24 hours, though this was doubled in some cases to 96 hours as will be discussed below.

6.1.3. The Experimental Stages

RH cycling was undertaken with the panels in four sequential stages;

1. Un-doped
2. Doped
3. Torn
4. Patched

Further details of the panel preparation and cycling procedure used for each panel configuration during the four experimental stages will be given below. A summary of the stages in the experiment and the number of RH cycles at each stage is provided in Table 6-1.

Panel Name	Gauge names	Stage 1: Number of Undoped RH Cycles	Stage 2: Number of Doped RH Cycles	Stage 3: Number of Torn RH Cycles	Stage 4: Number of Patched RH Cycles	Direction in which Tear Lengthened
Con1A	Con1A_Warp Con1A_Weft	3	2	3	2 (n.b. cycle time doubled to 96 hours)	Warp
Con1B	Con1B_Warp Con1B_Weft	3	2	3	2 (n.b. cycle time doubled to 96 hours)	Warp
Con1C	Con1C_Warp Con1C_Weft	3	2	3	2 (n.b. cycle time doubled to 96 hours)	Warp
Con1D	Con1D_Warp Con1D_Weft	3	2	3	2 (n.b. cycle time doubled to 96 hours)	Warp
Con2A	Con2A_Warp1 Con2A_Warp2 Con2A_Warp3 Con2A_Weft	1	1	3 (n.b. cycle time doubled to 96 hours)	3 (n.b. cycle time doubled to 96 hours)	Warp
Con2B	Con2B_Weft1 Con2B_Weft2 Con2B_Weft3 Con2B_Warp	1	1	3 (n.b. cycle time doubled to 96 hours)	3 (n.b. cycle time doubled to 96 hours)	Weft

Table 6-1: Stages of Relative Humidity cycling used in doped-fabric panel experiments. Each RH cycle took 48 hours unless otherwise stated.

Stage 1: RH cycling of the un-doped fabric

Once constructed, the panels of 9F1 Irish Linen were placed in the RH chamber without further modification; type 1 configuration panels underwent 3 RH cycles, while panels of type 2 configuration underwent 1 cycle.

Stage 2: Doping of the fabric and RH cycling of the doped-fabric

After RH cycling of the un-doped fabric, the panels were removed from the chamber into the ambient conditions of the lab and left for a minimum of 12 hours over night to acclimatise. They were then doped with 6 coats of the Randolph 9701 cellulose acetate butyrate dope, applied by brush.

The initial two coats of dope were diluted in acetone to improve penetration of the dope into the fabric. This practice is attested to within the historical literature, where thinning of the initial coats using cellulose thinners is recommended (see chapter 2.2). Acetone was used rather than commercial cellulose thinners to avoid the use of proprietary products with unknown and potentially changeable formulations. The volumes of dope used per coat were determined after initial testing, where it was found that insufficient volumes would not lead to even coverage and larger volumes an excessive saturation. A summary of the coats is provided in Table 6-2.

Coat Number	Dope Volume (ml)	Acetone (ml)	Direction	Drying Time (hours)	Application Method
1	15	15	Weft	1	Brush
2	15	15	Warp	1	Brush
3	30	0	Weft	1	Brush
4	30	0	Warp	1	Brush
5	30	0	Weft	1	Brush
6	30	0	Warp	1	Brush

Table 6-2: Dope coating process

After doping the fabric panels were left for 48 hours in ambient conditions before being returned to the humidity chamber for RH acclimatisation to low RH conditions and cycling as performed in the case of un-doped fabric. Configuration 1 panels underwent 2 cycles, while panels of type 2 configuration underwent 1 cycle.

Stage 3: Tear simulation and RH cycling of torn doped-fabric

The frames were removed from the humidity chamber and a tear simulated in the material by cutting the material using a scalpel. Tears were cut along the central axis of a panel so that the tear opened across the direction being measured by the central strain gauge in both configurations (Figure 6-4). Tears were started 10mm away from the edge of the acrylic frame and stopped 5mm short of the panel centre. In the case of Panel Con1_D, no tear was cut, but instead the panel was left unaltered to act as a control.

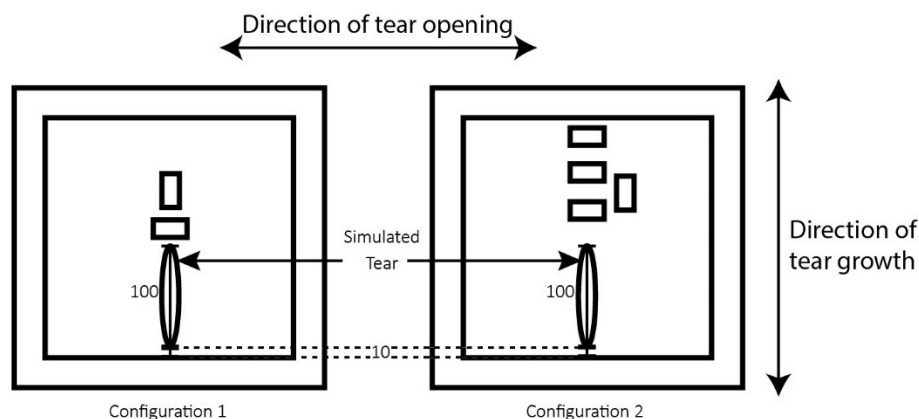


Figure 6-4: The location of simulated tears in the fabric panels (diagram is not to scale, and values are dimensions in mm)

After the tear was cut, the panels were returned to the humidity chamber for further cycling as per the previous two steps. Both panel configurations underwent 3 cycles but in the case of configuration 2 panels, the cycle time was increased to 96 hours to allow more time to observe the tear behaviour.

Stage 4: Tear patching and RH cycling of the patched doped-fabric

In the case of configuration 1 panels, three different types of patches were applied to the different panels (Figure 6-5 and Figure 6-6). The Con1A patch was a diamond shape running the length of the tear but stopping approximately 5mm short of covering the tips of the tear. It was designed to cover as little of the material surrounding the tear as possible, only being applied to areas that had visibly distorted after the tear opened.

Panel Con1B was patched using two separate, smaller patches at each end of the tear, each 10mm long, and leaving the centre section un-treated. The patches again did not cover the tip of the tear, but stopped 5mm short of covering the tip. The final panel to have been torn, Con1C, was patched with a square piece of fabric, 10x10mm, bridging the centre of the tear. This meant it did not approach the tear ends.

For all Con1 patches an initial coat of dope diluted 50:50 in acetone was brushed onto the patches and dried to provide an impregnation. After this they were placed over the respective tear area and a total of 4 dope coats were applied each 1 hour apart, the first two being diluted 50:50 in acetone. The small size of the fabric pieces made controlling the exact amount of dope used more difficult when trying to ensure an even and consistent saturation of the material. The volume of dope was therefore not closely controlled but brushed on until the patches appeared saturated as is done by Science Museum conservators, with care being taken not to brush over the patch edges.

For panels Con2A and Con2B, the tear was patched using a technique more comparable to that used on the aircraft by Science Museum conservators (see chapter 3.3). A patch of 9F1 Irish Linen measuring 60x110mm was prepared and impregnated with 9701 Randolph Butyrate dope diluted 50:50 in acetone. Once dried it was laid over the tear so that it extended beyond the tear tips by 5mm at each end, and adhered in place using 4 coats of Randolph 9701 cellulose butyrate dope, the first two of which were diluted in acetone and 1 hour between each coat. A total of 8ml of solution was used for each coat so that a consistent volume of solution was used for the area of patch to that used when doping the entire panel area in stage 2.

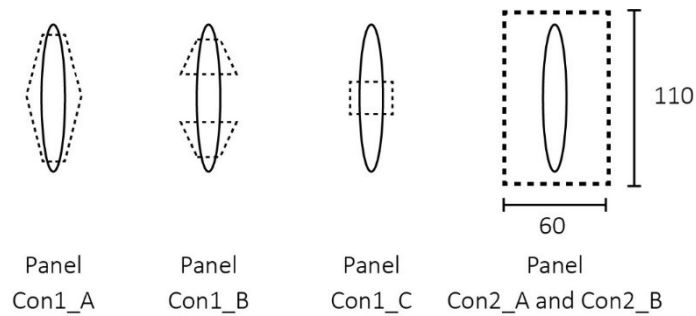


Figure 6-5: Patch shapes used for treating simulated tears. Patches used on panel Con2_A and Con2_B are representative of those used at the Science Museum previously. Those used on Con1 type panels are new tear proposals.

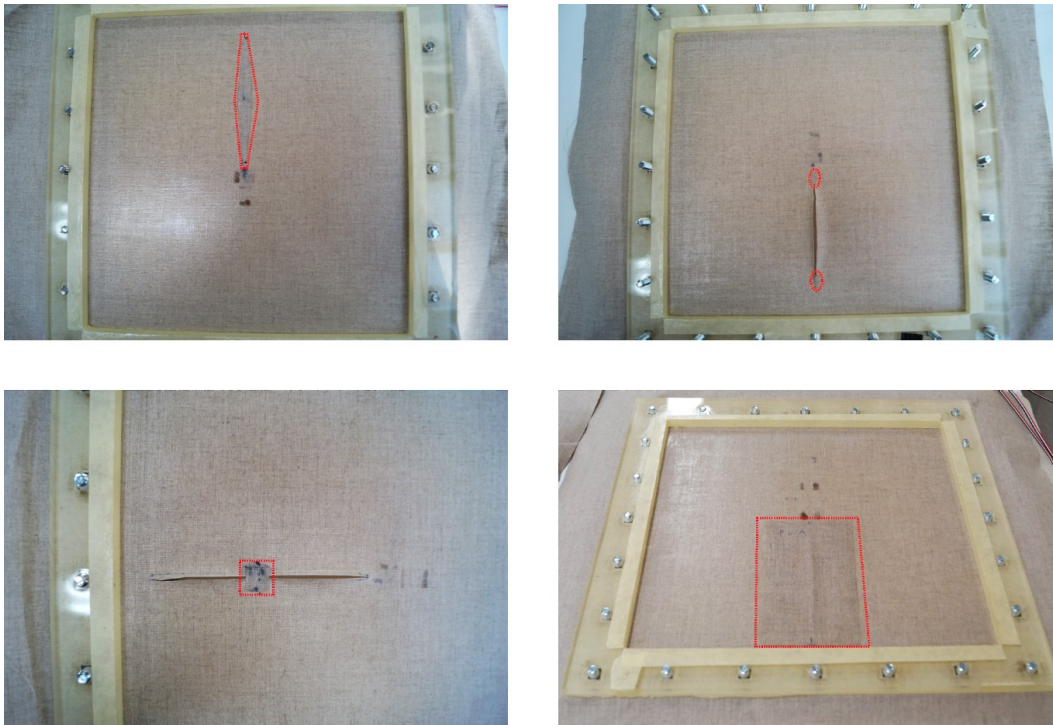


Figure 6-6: Patches applied to the fabric panels. From top left to right Panel Con1A, Con1B, Con1C and Con2A (patch area highlighted with dotted red line)

After patching, the panels were returned to the humidity chamber for RH cycling; type 1 configuration panels underwent 2 cycles, while panels of type 2 configuration underwent 3 cycles. For both panel configurations the RH cycling time was 96 hours.

6.2. In-Situ Use of Resistance Strain Gauges on Gallery

Resistance strain gauges were attached to two aircraft on display in *Flight*, the JAP Harding Monoplane and Vickers Vimy as these provided the opportunity to study areas around both undamaged fabric, and around areas of tearing which could then be patched. There were several important requirements when selecting sites for *in-situ* monitoring which were that locations had to be:

- Out of reach of public interference.
- In a location where the weight of the P3 monitoring box and Hanwell environmental monitor could be supported within 1m of the gauges.
- Provide access to both the interior and exterior surface of the fabric so that pressure could be exerted to both sides when securing the gauges, and thus lessen the risk of damaging the material further.
- Accessible enough to enable access with a mobile tower, scaffold platform or other stable surface for working on as using a ladder was not considered sufficiently stable when adhering the strain gauges.

The gauges at each location have been named according to the location designation and the direction in which strain was measured. Where multiple gauges were adhered in the same orientation around a tear but at increasing distances from the tip, the gauges have been given a number with increasing number indicating greater distance from the tear tip. A list of the gauges are provided in Table 6-3 and images of their locations on the JAP Monoplane and Vickers Vimy in Figure 6-7 and Figure 6-8 respectively.

The directions of the fabric weave on the Vickers Vimy were assigned directions, X for spanwise from wingtip to wingtip and Y for chordwise across the wing as the weave was aligned with these features of the aircraft. In the case of the JAP Harding Monoplane the weave is set at 45° to these features and so the X and Y directions were arbitrarily assigned (Figure 6-7).

There was a thick layer of museum dust on all the aircraft surfaces studied which was removed with a microfibre cloth and then lightly swabbed with distilled water to create a clean surface before bonding the gauges. The strain gauges were attached using MBond200 adhesive as for the laboratory prepared panels.

Aircraft	Location	Gauge designation	Area Patched (Y/N)
JAP Harding Monoplane	Starboard wing upper surface exterior	JAP_Ext_X JAP_Ext_Y	N
JAP Harding Monoplane	Starboard wing upper surface interior	JAP_Int_X	N
JAP Harding Monoplane	Unattached control	JAP_Con	N
Vickers Vimy	Upper port wing exterior	VV_UPW_X VV_UPW_Y	N
Vickers Vimy	Fuselage, cockpit area interior	VV_Cp_X VV_Cp_Y	N
Vickers Vimy	Lower port wing surface, interior	VV_LPW_Y1 VV_LPW_Y2 VV_LPW_Y3 VV_LPW_Y4	Y
Vickers Vimy	Lower starboard wing, interior	VV_LSW_X1 VV_LSW_Y1 VV_LSW_Y2 VV_LSW_Y3	Y
Vickers Vimy	Main fuselage interior surface	VV_MF_X1 VV_MF_X2 VV_MF_Y1 VV_MF_Y2	Y

Table 6-3: A list of the strain gauges and their locations on the JAP Monoplane and Vickers Vimy on *Flight*

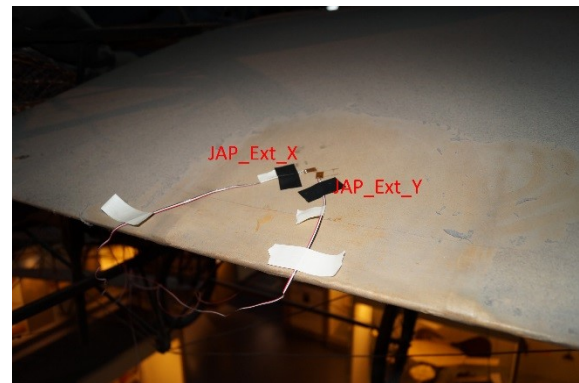
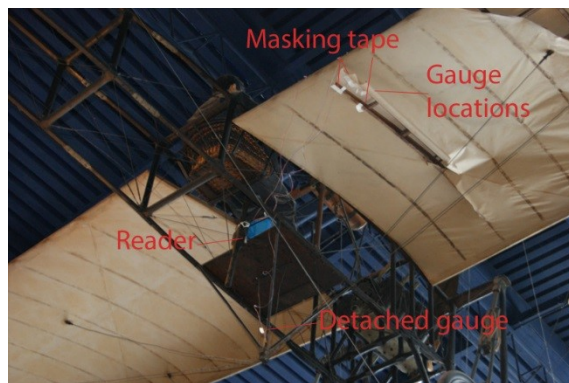


Figure 6-7: Left the location of strain gauges on the JAP Harding Monoplane in *Flight*. Right, the strain gauges adhered to the upper surface of the JAP monoplane.

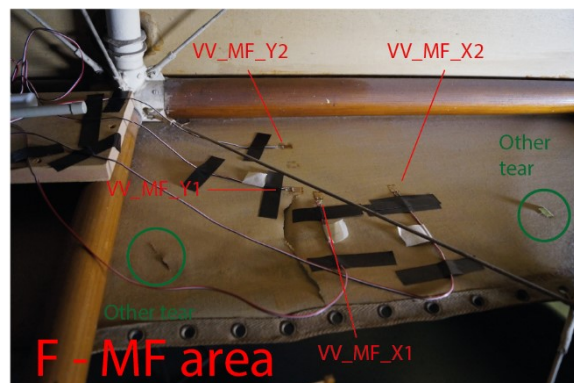
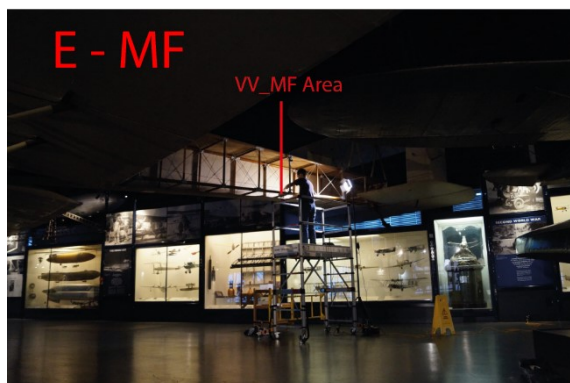
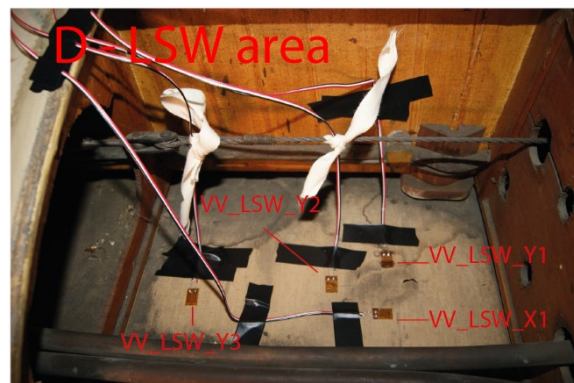
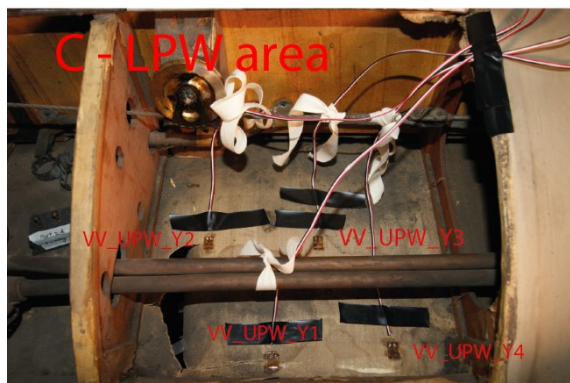
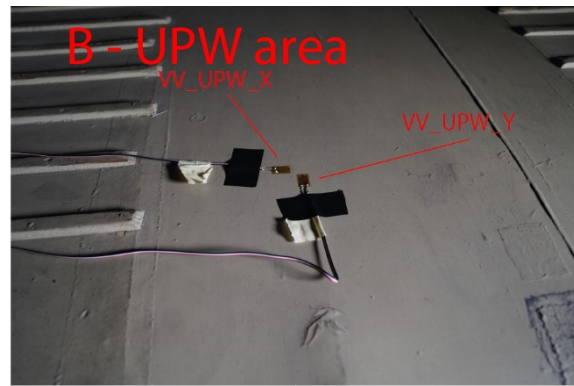


Figure 6-8: The location of strain gauges attached to the Vickers Vimy. From top left to right; (A) the locations in the Cockpit, upper port wing and lower port wing, (B) close up of the gauges attached to the upper port wing, (C) close up of gauges attached to the lower port wing, (D) the gauges attached to the lower starboard wing, (E) the location of gauges in the mid-Fuselage section, (F) close up of the gauges in the mid-Fuselage section

One site on the JAP Harding Monoplane was monitored, the upper surface of the starboard wing directly above the large tear which had opened in the lower surface (Figure 6-7). This surface was chosen as it was undamaged and the tear in the lower surface enabled access to the interior side of the upper wing. Two gauges were attached to the outer surface, one in each fabric direction X and Y respectively, and one to the interior surface in direction Y. A fourth gauge was not attached to the fabric but, having been prepared was then left hanging loose to act as a control.

Five locations of the Vickers Vimy were monitored using strain gauges (Figure 6-8). Two of the areas were chosen as there did not appear to be any tears in the immediate vicinity and they could be monitored simultaneously. One location was an area of the fuselage to the rear of the cockpit, called VV_CP, where access to the unpainted, inner side of the fabric was possible. Due to access difficulties from the surrounding aircraft structure the gauges had to be secured very close to the edge of the fabric where the cross-section had been cut away.

The other undamaged location chosen was the upper surface of the port wing (VV_UPW) as, although access to both sides of the fabric was not possible, an inspection of the area indicated it was still robust enough for pressure to adhere the gauges without risking the material. Part of the reason this area was more robust than others may be that it had extra structural elements which seemed designed to enable access for wing walking and inspection, and it should be noted that whilst this enabled attachment of gauges it may not be a very representative area for the entire structure.

The other three areas of the Vickers Vimy monitored were around tears in the main fuselage (VV_MF), lower port wing (VV_LPW) and lower starboard wing (VV_LSW) which were monitored to investigate strain behaviour around tears, and to assess the behaviour of such areas after patching. The tear in the fuselage section was a relatively straight tear, running across the width of the fuselage. The tears in the port and starboard wings, in contrast, were very irregular. The port wing tear was a large horse shoe and gaped open without support. The tear in the starboard wing, in contrast was rounded in shape and stayed reasonably well aligned even without any support.

The tear areas in the fuselage and lower wing surfaces were monitored for several weeks before a patch was applied to the affected area by a Science Museum conservator following the methodology described in chapter 3.3. Data from the strain gauges in the patched area was then collected for several further weeks. No attempts were made to control or modify the environment in the test areas throughout the monitoring.

6.3. Sampling of Historic Materials

6.3.1. Technical File

A description of the samples taken from materials found in the technical files as well as from aircraft on display in gallery conditions on *Flight* will be documented here. The technical file materials were the first material sampled for analysis to identify the materials used in their manufacture (chapter 7). For this a total of 15 samples measuring 1x1cm were taken. A summary of the fabrics found in the technical files as well as the samples taken from them for this initial analysis is provided in Table 6-4. More detailed descriptions and images showing the location from which samples were taken is provided in the following sections.

When naming samples a system was used to distinguish the following levels of information:

XX(X)_YY_NA, where:

XX(X) = The Aircraft (The initials or first few letters of the aircraft name)

YY = The Source (Gallery (GS) or Technical file(TF))

N = The fabric number where multiple pieces were kept in a technical file (1, 2, 3... n)

A = Sample letter to distinguish samples (A, B, C...). Paint layers separated from the fabric substrate were given their own designation Pa.

For example JAP_TF_2B refers to a sample taken from fabric piece 2 of the JAP Harding Monoplane's technical file.

Following this first phase of testing, the technical file fabrics were also sampled for tensile testing samples which required larger amounts of material (Chapter 8). For this process squares of material were cut from which individual tensile samples were then cut. A random direction, X and Y, was also assigned to the fabric since the direction of the warp and weft was unknown. The images of the technical file fabric in the sections below show the locations from which tensile test materials were taken and are annotated to show the X and Y direction.

Before each phase of sampling was undertaken a research proposal was submitted to the curatorial and conservation department to explain the purpose of sampling, the expected research benefit and the amount of material required. This is done to ensure sampling within the museum is conducted in-line with museum policy and is justifiable within the institutions research aims and objectives. It also ensures museum and conservation ethics are considered before samples of historic materials are removed as per guidelines for the taking of samples from heritage objects (Quye and Strlič, 2019).

Aircraft	Source	Fabric Number	Fabric Description	Sample Title	Sample Description
Cody Bi-Plane	Technical File	1	Irregular shape. One side has the remains of a cream paint. The fabric is overall a light brown and flexible. At one end the fabric is a darker brown and stiffer.	CBi_TF_1A	Light brown fabric. Flexible. No distinguishing features between the internal and external surfaces.
				CBi_TF_1B	Dark discoloured fabric on both sides. Stiff. Small paint flakes on the presumed exterior. Cream colour.
				CBi_TF_1Pa	Paint delaminated from fabric. Smooth on the outer face, rough on the interior.
JAP Monoplane	Technical File	1	Piece 1 is the smaller, roughly rectangular piece of fabric. It is an even dark brown, almost black, on one side, which appears to be a coating that is lifting in places and is presumed to be the exterior. The reverse is a more uneven, lighter brown colour.	JAP_TF_1A	Sample from the smaller piece of fabric. It is darker on one side, presumed to be the exterior.
JAP Monoplane	Technical File	2	The larger piece of fabric of the two in the JAP file. It is irregularly shaped. One side is a mottled, off white colour. The other side has the same white colour over large areas but also a dark brown/black coating in places. This coating has begun to delaminate in some areas.	JAP_TF_2A	Sample from the larger piece of fabric taken from a section with no surface coating. Stiff. White to cream on both sides. The fabric weave is visible.
				JAP_TF_2B	Sample from the larger piece of fabric taken from a section with the surface coating intact. Stiff. White to cream on what is presumed the interior, dark brown/black on the presumed exterior.
Roe Tri-plane	Technical File	1	A roughly rectangular piece of fabric. The reverse is a loose netting supporting a dark brown/black matt covering.	RT_TF_1A	The dark brown coloured covering is visible on both sides. On the presumed interior are fibres from the coarse netting supporting the covering.
Se5a Fighter	Technical File	1	A square piece of fabric. It is dark brown/red on one side where the warp is visible. The other side, presumed to be the exterior, has an even brown coating, with a silvery finish showing	Se5_TF_1A	Sample is brown/red coloured on both sides. The presumed exterior has a brighter red over approximately half the surface. The interior is an even dull brown.

Aircraft	Source	Fabric Number	Fabric Description	Sample Title	Sample Description
			through beneath in places. Around two edges the colouring is less even with brighter red areas. There are also some small holes along one edge, possibly where the fabric was attached to the frame.	Se5_TF_1B	The exterior is an even brown colour with a few silvery flecks showing through around the edges. The interior is a dull red and the weave is visible.
				Se5_TF_1C	The exterior is an even silvery colour. The interior is a dull red and the weave is visible.
Vickers Vimy	Technical File	1	The material is heavily creased from being stored folded inside the technical file. The material is quite stiff, and a dark, shiny brown on one side (probably the exterior) and lighter brown on the reverse where the weave is more visible. There is a darker strip of material down one edge.	VV_TF_1A	A sample from the edge with a dark strip of material. One side is a dark brown, the other a lighter brown with the fabric weave visible on both.
				VV_TF_1B	A sample from the edge of one of the failed creases. One side is a glossy, darker brown, the other a light brown. The fabric weave visible on both though most obvious on the lighter side.
Vickers Vimy	Technical File	2	A very light brown/off white colour fabric. Flexible and no feeling of stiffness.	VV_TF_2A	A sample from one of the three extra pieces in the technical file. Sample is a light brown on both sides with no distinguishing markings to determine the interior or exterior surface.
Vickers Vimy	Technical File	3	A very light brown/off white colour fabric. Flexible and no feeling of stiffness.	VV_TF_3A	A sample from one of the three extra pieces in the technical file. Sample is a light brown on both sides with no distinguishing markings to determine the interior or exterior surface.
Vickers Vimy	Technical File	4	A very light brown/off white colour fabric. Flexible and no feeling of stiffness.	VV_TF_4A	A sample from one of the three extra pieces in the technical file. Sample is a light brown on both sides with no distinguishing markings to determine the interior or exterior surface.

Table 6-4: Description of fabrics found in the Science Museum technical files and the 1x1cm samples taken from them for analysis. Descriptions are based on a visual inspection of materials and judgements as to flexibility are a subjective impression received from handling the material and the materials resistance to manipulation.

Antoinette

Two pieces of fabric were found in filing cabinets in the conservation department office at South Kensington. These pieces had unfortunately become separated from the technical file at some point or had never been added. They were found late in the research programme when most chemical analysis for other technical file materials had already been completed, meaning they were not sampled at the same time as other technical file material. The samples are fairly pliable and, barring the creases, lie flat without curling up. The two samples are also fairly robust, again with the exception of the creases where tears have occurred.



Figure 6-9: Fabric samples from the Antoinette Monoplane Technical File

Fabric piece 1 consists of a brown, square piece with a crease running across its length, possibly the result of being folded for many years within a museum filing cabinet though it may also have been folded around a structural element of the aircraft. There is a second smaller crease across one corner. There is significant staining around this crease and some failure where the fabric is beginning to break into two. Only this piece was sampled. A total of 4 samples were taken for the purposes of tensile testing, which were also used for chemical analysis.

Fabric piece 2 has almost separated into two. Down the centre of this piece is a brown strip with small holes, possibly attachment points to the airframe. This piece is also heavily stained and marked. Both pieces have been annotated with the same notes in pen stating, '*Piece of Michelin rubber proofed fabric from Antoinette Monoplane, Jw(?) .1926-541*'

Cody Bi-Plane

One piece of fabric was found in the Cody Bi-Plane technical file. The piece is of an irregular shape and has several creases. The larger part of the material is a light brown colour and feels fairly flexible and robust when handled, though there are some areas of damage to the weave. A large area of the material also has a cream paint, though this is delaminating from the surface, and it is presumed this is the exterior side.

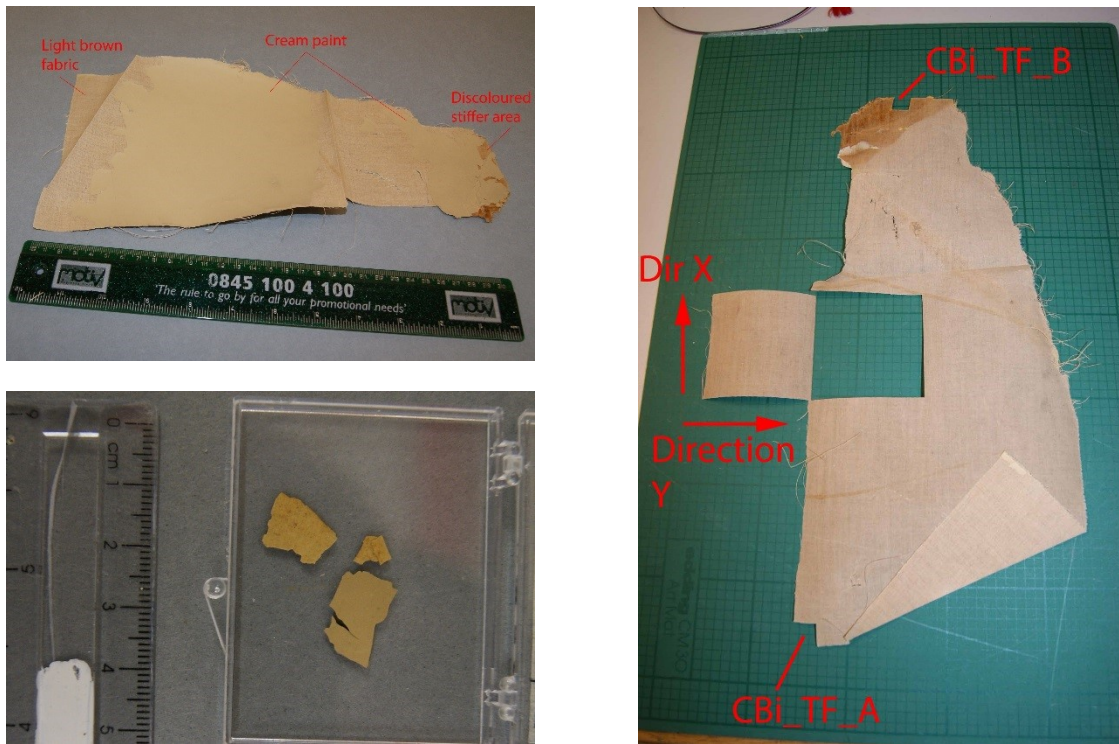


Figure 6-10: Fabric samples from the Cody Bi-Plane Technical File and bottom left pieces of delaminated paint found in the fabric

A small end section of the material is a dark brown colour and feels stiffer to handle. This are also the remains of a cream coloured paint over this end section which extends across the brown area and into the light brown fabric. This layer has cracked and delaminated in places, and some loose paint flakes were found inside the folded fabric when opened.

JAP Monoplane

Two separate pieces of fabric were found within the JAP Monoplane technical file within the same envelope. The first piece, JAP_TF_1, was a smaller, rectangular shape. It had a light to dark brown colour on one side, and was a more consistent dark brown on the other. This piece was very brittle and weak.

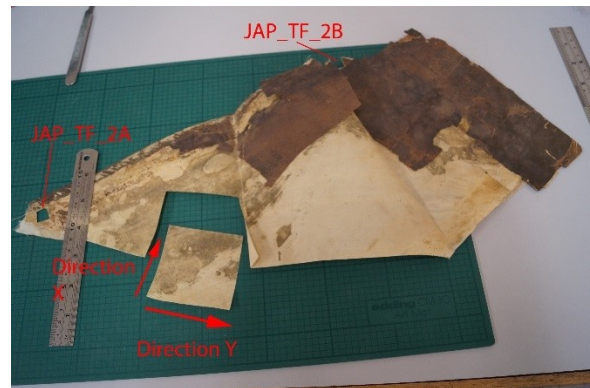


Figure 6-11: Top: Fabric samples from the JAP Monoplane Technical File. Bottom loose piece of coating, JAP_TF_Pa, found in fabric folds

The second piece of fabric, JAP_TF_2, was irregularly shaped and heavily creased from being folded over itself. The surface finish of this piece of material was very inconsistent. A dark brown coating appeared to cover a large proportion of this fabric, but was delaminating in many parts. This coating visually appeared very similar to that of the other piece of fabric in the envelope. The piece of fabric was robust, though great care was needed in unfolding the creased sections to prevent further delamination of the surface coating. It is presumed that the side with the delaminating surface coating is the exterior. A loose piece of the brown coating was also found in the folds of fabric piece 2 which was retained for analysis and labelled JAP_TF_Pa.

Roe Tri-Plane

A single, irregular sized piece of material was found in the Roe Tri-Plane technical file. The material was a smooth, dark brown on one side. The reverse was a very loose netting, rather than closely woven fabric.

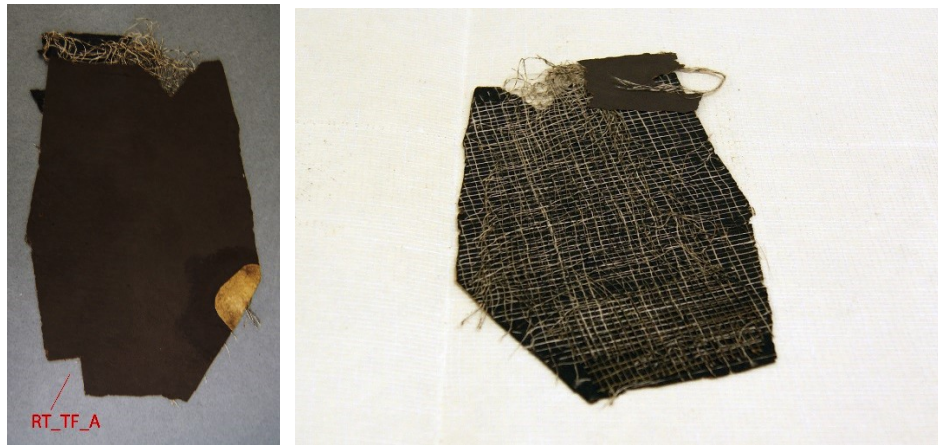


Figure 6-12: Fabric sample from the Roe Tri-plane Technical File

Se5a Fighter

A single square piece of fabric was found in the folder of the Se5a Fighter which was heavily creased in both directions approximately through its centre. Two edges had been cut with pinking scissors, whilst the other were straight. The straight edges also had small holes and a different surface finish compared to the larger area of fabric centre, suggesting that these areas were perhaps where it had been attached to the aircraft frame. There was what appeared to also be a second layer of fabric in this region, indicating the use of tape to further re-enforce the seams.

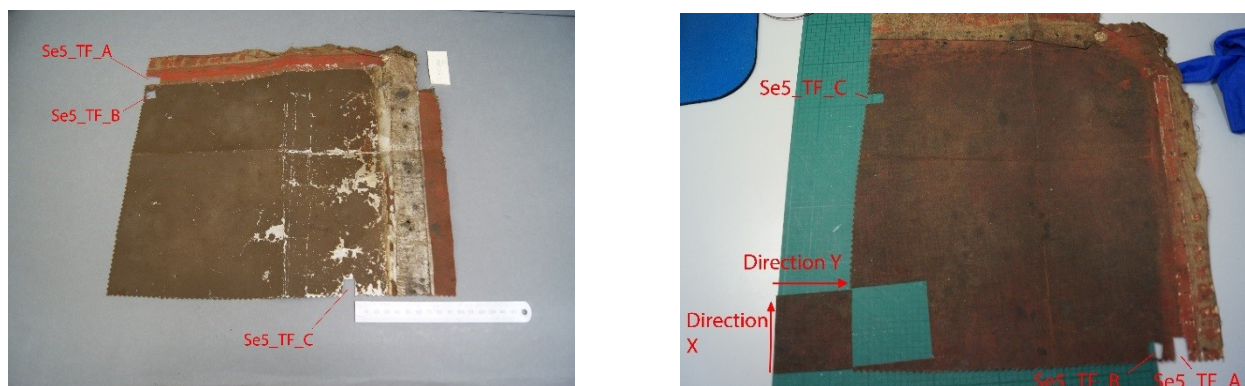


Figure 6-13: Fabric samples from the Se5a Aircraft

One side of the material was a dark brown over the majority of the surface, but there was a lighter red along the smooth edges and the weave was visible. The reverse was generally a dark brown, but again there was red along the smooth seams. There was also a silvery surface finish which appeared to be underneath the dark brown coating.

Vickers Vimy

A total of four separate pieces of material were found in the Vickers Vimy technical file. Piece one was found in its own envelope separate from the other fabric samples and had been folded so was heavily creased. It felt quite brittle when handled and was impossible to lie flat. One side was a dark, glossy brown colour, whilst the reverse was a lighter brown. There was a darker colour along one edge. Some smaller, detached pieces were also found in the envelope.

In a separate envelope three pieces of fabric were found of different sizes which were a much lighter colour compared to piece 1 and appeared to be similar on both sides. These were numbered 2, 3 and 4.

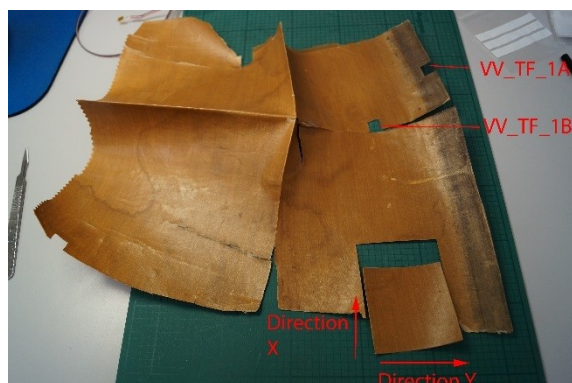


Figure 6-14: Fabric pieces from the Vickers Vimy Technical File. Piece 1 (top) was found in a separate envelope to pieces 2-4

6.3.2. Gallery Samples

As part of sampling the aircraft currently on display an official request was sent to the curatorial team as part of the Science Museum's process for sampling and it was determined to only sample around areas of failure to limit the risk of further damage. Samples were cut from the doped-fabric skin with scissors by the author. This section will describe the areas of damage and the samples taken.

Aircraft	Area of Damage	Sample Description
Antoinette Monoplane	A small tear in the starboard side of the fuselage.	The sample is rectangular. It has a dark blue exterior and dark brown interior where the weave is visible.
Cierva C30 a	A flap of loose fabric on the starboard stabiliser. This appears to have formed due to impact damage resulting in a hole in the material.	The exterior has green paint though this has flaked off in many places and cracked. The fabric below the paint is red coloured. The interior fabric surface is the same red colour.
JAP Monoplane	A large tear running the length of the starboard wing.	The material is a light brown on the interior surface and a slightly darker and shinier brown on the exterior. It is heavily curved.
Pterodactyl	A tear in the starboard wing.	The sample is triangular in shape. It is red coloured on the interior and the weave is visible. The exterior is a smooth silvery finish where the weave is not visible.
Supermarine S6B	A tear on the starboard side of the empennage section.	A rectangular shape. A dark blue, smooth finish on the exterior and a red on the interior. The weave is also visible on the interior surface.
Vickers Vimy	A hole in the top surface of the empennage section.	Two pieces were sampled. Both have a smooth, cream coloured exterior surface. On the interior the weave is visible and a light brown colour.

Table 6-5: List of aircraft from which doped-fabric aircraft was sampled from the Flight Gallery of the Science Museum

Antoinette Monoplane

A tear had opened in one side of the aircraft fuselage from which a rectangular piece was sampled. This piece had a dark blue paint layer on its external face and the interior was a dark brown colour, where the weave of the textile was visible. The piece was curved slightly, the interior under compression and the exterior under tension.



Figure 6-15: Fabric samples from the Antoinette Monoplane fuselage on display in *Flight* at the Science Museum

It should be noted that the other areas of the Antoinette Monoplane fabric in the empennage, which had not been painted, and therefore are closer in appearance to that found in the museum files, were not damaged and so were not be sampled.

Cierva C30a

A small hole had been punched in the starboard stabiliser resulting in a circular hole with a loose flap of material which had curled inside and was approved for sampling. The size of the piece was too small to allow for tensile

testing so was only used for analysis to identify the materials of construction. The piece was red coloured on the inside and had a green/brown external paint layer with large areas of loss. The piece was heavily curled and would not lie flat without weights.

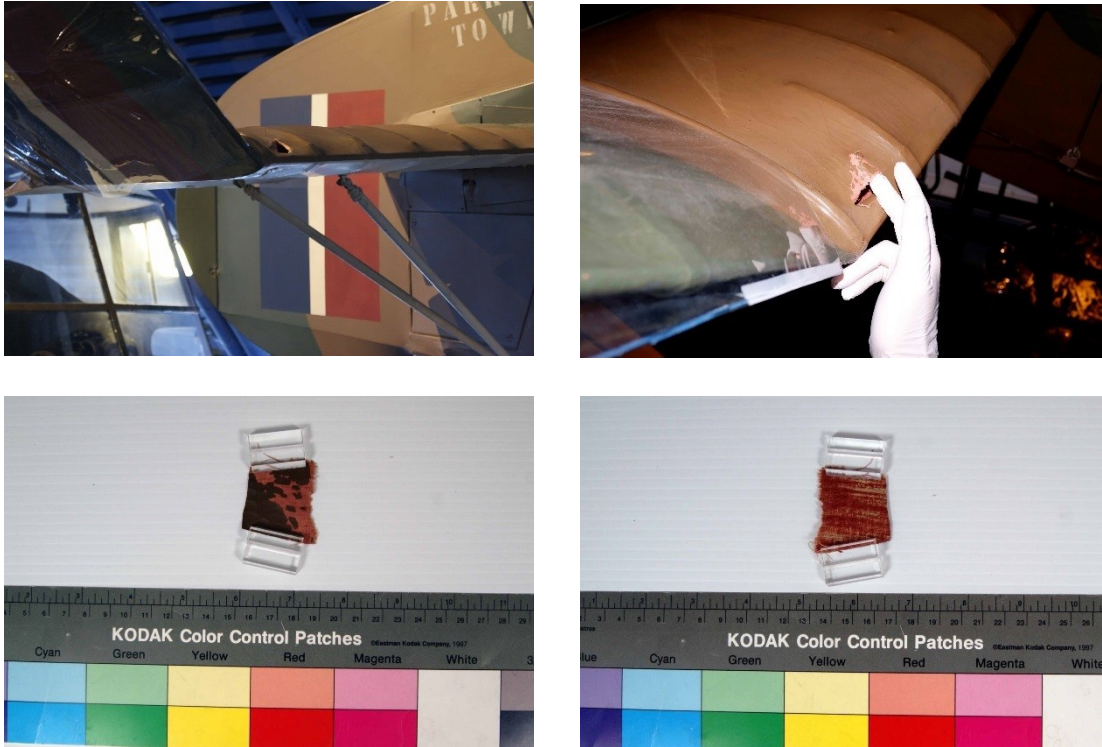


Figure 6-16: Location of damage and fabric samples from the Cierva C30a on display in *Flight* at the Science Museum

JAP Monoplane

A large tear had opened in the starboard wing running the length of the aircraft from the trailing end of which a rectangular piece was sampled. The sampling area was limited by access as work had to be conducted from a mobile lifting platform which could not approach close in due to the location of showcases. The piece obtained is heavily curled in upon itself, the exterior of the fabric being under compression and the interior under tension. The material is a light brown on both sides, though the exterior appears slightly darker than the exterior.

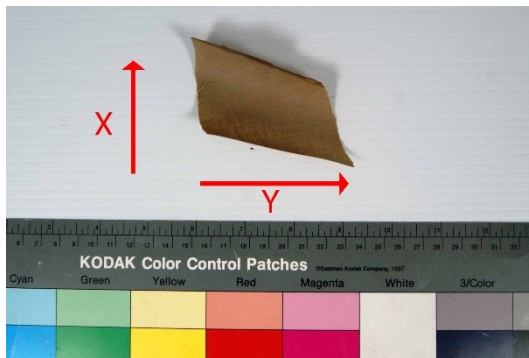
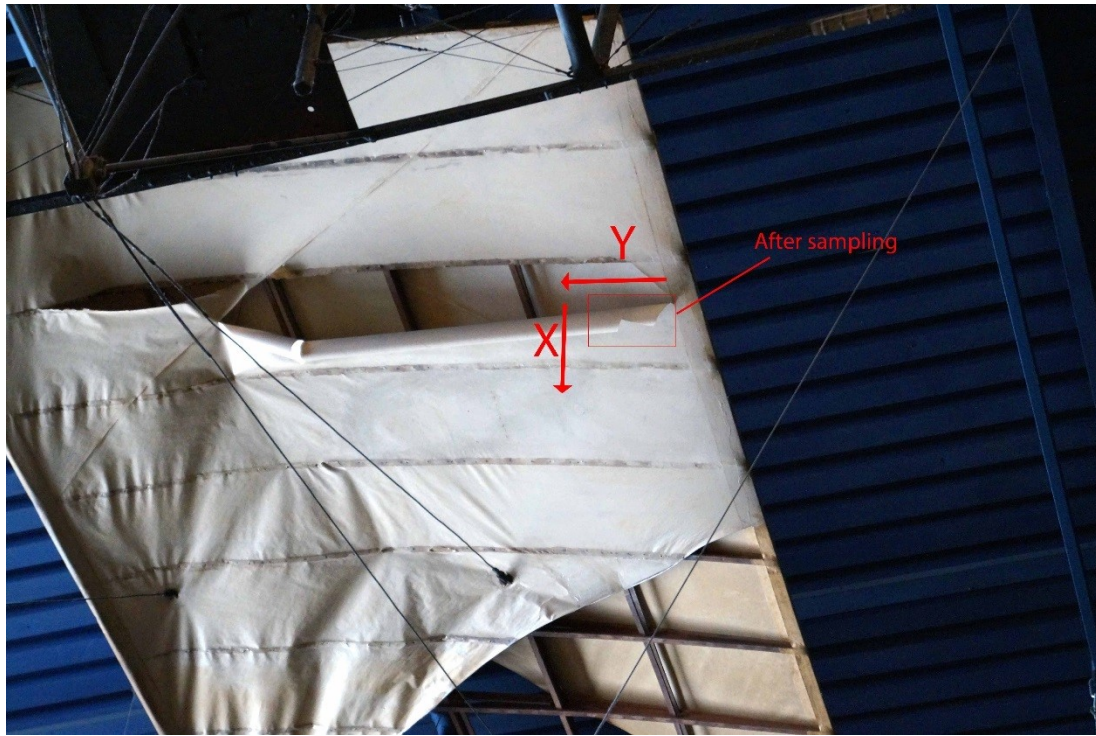


Figure 6-17: Location of damage and fabric samples from the JAP Monoplane on display in *Flight* at the Science Museum

Pterodactyl

A tear running the length of the port wing was sampled. The exterior is a smooth, even silver colour while the interior has a mottled red appearance, and is pale brown where the weave of the fabric is visible.

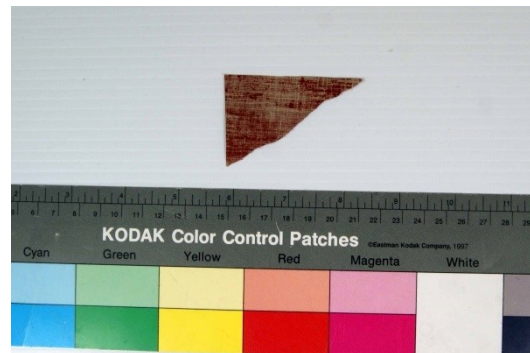
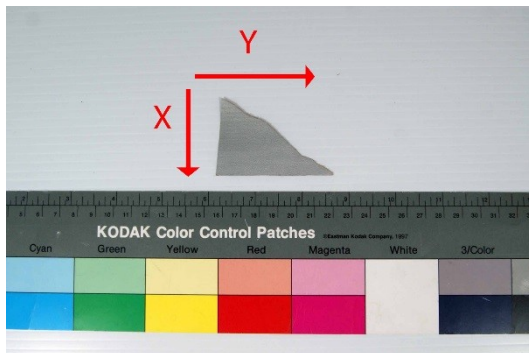
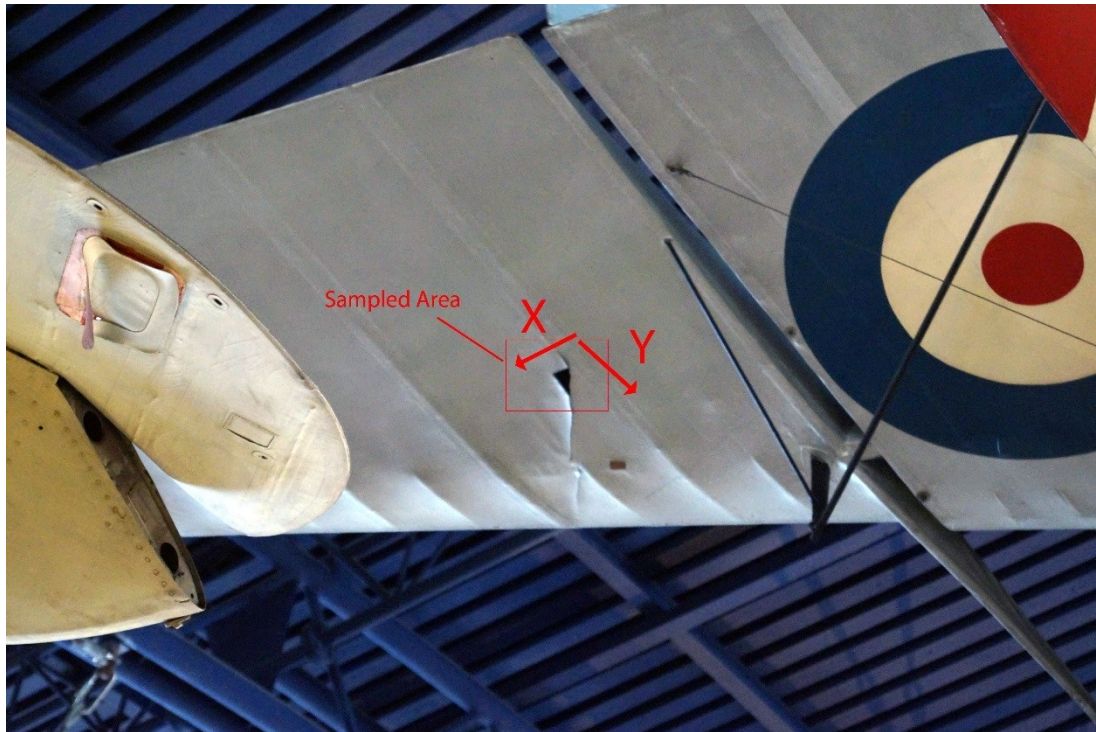


Figure 6-18: Location of damage and fabric samples from the Pterodactyl on display in *Flight* at the Science Museum

Supermarine S6B

A tear in the tail section which had been previously conserved was sampled though only a piece from the blue section where the tear had opened most was taken as it was feared that sampling nearer the other end of the tear tip might cause further damage.

The exterior of the sample was a dark blue, even colour. The interior had an even red colour, though in places the weave and brown of the fabric did show through. The piece was curved slightly, the interior under compression and the exterior under tension.



Figure 6-19: Location of damage and fabric samples from the Supermarine S6B on display in *Flight* at the Science Museum

Vickers Vimy

Large tears had opened on the upper surface of the rear empennage section and, although not the only area of damage available to sample, it was the least visible section of the aircraft as currently displayed so considered most suitable for sampling. As access to the tear area was good and the tear was so extensive, it was decided to take several slightly smaller samples from two slightly separate areas so as to limit the impact of sampling on any one location.

The pieces removed from the Vickers Vimy were curved slightly, the interior under compression and the exterior under tension. The exterior had a cream, even surface finish whilst the interior was a dark brown and the weave was clearly visible.

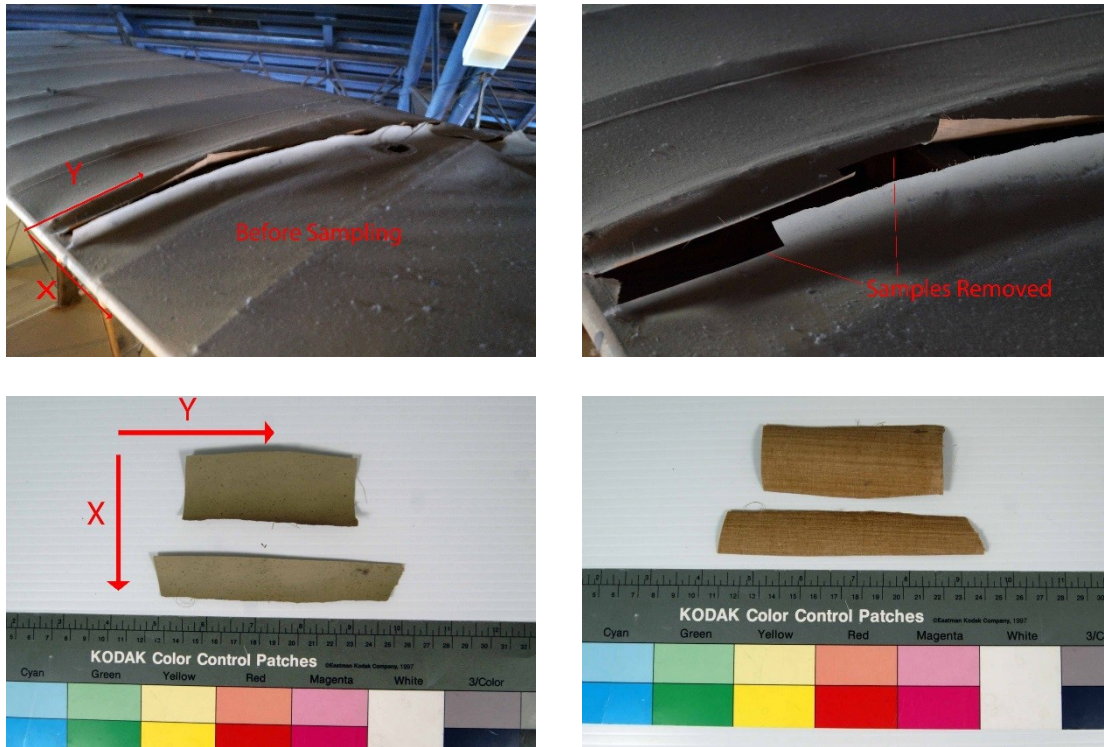


Figure 6-20: Location of damage and fabric samples from the Vickers Vimy on display in *Flight* at the Science Museum

7. Material Identification

7.1. Introduction

The review of the doped-fabric aircraft at the Science Museum in chapter 3 has highlighted gaps in knowledge as to what materials the objects are constructed from. This is in large part due to undocumented treatments that occurred during the 1960's and 1970's when most of the aircraft currently on display appear to have undergone extensive restoration. This may have involved re-covering and then subsequent re-doping, patching and painting over the years, though only limited details are kept in the museum records (chapter 3.1).

This gap in knowledge makes it difficult to evaluate the aircraft as doped-fabric structures. A review of the historic materials and practices for making and maintaining doped-fabric in chapter 2 established that certain materials, structures and practices would be expected in a historic doped-fabric aircraft. This comprised a linen or cotton fabric then treated with a cellulose ester type dope. Certain types of dope, such as those pigmented with iron oxide, aluminium powder or left clear, might also be layered together.

An analysis of the material composition and construction of the Science Museum doped-fabric aircraft is therefore required to provide information with which the material form of the aircraft may be judged against their historic context. Important information includes establishing the type, or if indeed any dope was used, the presence of additives, and the structure of any multi-layered dope-fabrics.

It should be emphasised that establishing the materials used is not in itself an answer to such questions as to how original or authentic the doped-fabric aircraft at the museum are. As covered in chapter 4, these concepts are complex and subjective issues, and may have no objectively 'correct' answer. Rather this study aims to provide information with which the appropriateness or otherwise of the materials comprising the Science Museum doped-fabric aircraft in their current form and context may be considered, and hence improve conservators' understanding as to the value of such materials in their current context and how appropriate various interventions might prove.

7.2. Sample Preparation

7.2.1. Modern References

A selection of aircraft fabrics and dopes which are currently commercially available were purchased from LAS Aerospace. The materials obtained were:

- 9F1 Irish Linen
- 7F8 Aircraft Cotton
- Randolph A9701 Clear Tautening Butyrate Dope
- Randolph 210 Nitrate Dope
- Red Neogene Dope
- Tri-phenyl phosphate

These modern reference materials were purchased for several purposes. Firstly, the 9F1 Irish Linen and Randolph A9701 butyrate dope are used in the Science Museum patching process, and so an analysis of these to establish their composition is important to verify what the aircraft have been conserved with. Also, as discussed in chapter 6, it was planned to use the modern doped-fabric materials as surrogates in controlled experiments using the acrylic frames. Understanding the composition of these materials, therefore, and having a comparison to the historic doped-fabric materials was required.

Films of the dopes without a fabric substrate were prepared by casting the dope onto Melinex sheets (Polyester film) and allowing these to air dry in ambient conditions. Samples of the un-doped 9F1 linen and 7F8 cotton were cut as 1x1cm pieces directly from the rolls of fabric as supplied.

Panels of the 9F1 linen and 7F8 cotton doped with the three dopes were also prepared according to the method described in chapter 6.1 for preparing doped fabric panels. From these 1x1cm samples were cut in line with the weave as done for the fabrics for chemical analysis.

7.2.2. Technical File

Samples were cut from the technical file material as described in chapter 6.3.1. Samples were 1x1cm in size. Where there appeared to be different surface finishes or a non-homogenous material multiple samples were taken for analysis.

7.2.3. Gallery Samples

Doped-fabric on gallery were sampled according to the method set out in chapter 6.3.2. It is worth re-emphasising that material was only taken from areas around an existing tear so that no new area of damage would need to be introduced, and this limited the areas that could be sampled.

The size of samples varied somewhat as the remaining material left over after taking samples for tensile testing (chapter 9) was used. This could result in large enough pieces for 1x1 cm pieces to be used as for technical file materials, but was not always possible.

7.3. Experimental

A range of analytical techniques, including Fourier Transform Infra-Red - Attenuated Total Reflectance (FTIR-ATR) spectroscopy, Raman spectroscopy, X-Ray Diffraction (XRD) and X-Ray Fluorescence (XRF), were applied to generate as full a picture of the materials used in constructing the doped-fabric aircraft as possible. A combination of analytical techniques is often required in characterising materials since different analytical techniques will provide information about different aspects due to the different strengths and limitations in how they operate (Desnica *et al.*, 2003). An overview of the strengths and limitations of the analytical techniques used and the experimental process will be provided here. A more detailed description of the theory underpinning the experimental techniques may be found in Appendix C.

7.3.1. Optical Microscopy

Microscopy is an important tool for studying the construction of the doped-fabrics for determining the number and types of dope and paint layers present, and is an established technique in the conservation of painted surfaces (Weilhammer, 1995; Townsend and Keune, 2006). It may also be used to identify between types of fibre, being able to distinguish between different types of cellulosic fibres as well as artificial ones (Mayer, 2012; Suomela, Vajanto and Räisänen, 2017).

Optical microscopy was carried out using a Zeiss AxioScope A1. Micrographs of cross sections and woven surfaces were taken using reflected light. The edges of samples cut for tensile testing (Chapters 8 and 9) were used for imaging the cross sections without further mounting or preparation. The edges of cross section samples were thresh-held and the backgrounds darkened using Photoshop image editing software to enhance the sample features.

Micrographs of fibres to distinguish between fabrics were taken using transmitted light in bright field mode. Samples of the 9F1 Irish Linen and the 7F8 Aircraft Cotton before doping were prepared by mechanically separating a few fibres using fine tweezers, and then mounting these onto a slide using a drop of water. The individual fibres of doped and historic materials could not be separated mechanically in the same way due to the

effect of the doping process but, after tensile testing (chapter 8), it was found that some of the fibres were pulled somewhat free of the dope matrix and could be imaged.

Although cross-polarised light is frequently used for fibre identification, it was found in this context that bright field imaging proved more suited for imaging the doped samples, which is attributed to the problems of imaging fibres still trapped in amongst bundles of other fibres from the doping.

7.3.2. Fourier Transform Infra-Red Spectroscopy – Attenuated Total Reflectance (FTIR-ATR)

Fourier Transform Infra-Red (FTIR) spectroscopy has been used extensively in conservation research for identifying and studying a range of materials, including plastics, textiles and pigments (Learner, 1998; Derrick, Stulik and Landry, 1999; Garside and Wyeth, 2006; Chércoles Asensio *et al.*, 2009; Nel, Lau and Baybrook, 2011) (see chapter 5.2). The technique may be coupled with Attenuated Total Reflectance (ATR), using a crystal to reflect the light beam along the underside of the sample. This means the radiation never penetrates the sample, but interacts with it in the top 3-4µm, limiting it to surface analysis of samples (Mojet, Ebbesen and Lefferts, 2010; Cucci, Bigazzi and Picollo, 2013). The technique is of interest within conservation since it has the potential to be used non-destructively on objects in-situ. Where samples do need to be removed, it still offers an advantage for historic materials as samples do not need to be powdered and encapsulated in KBr pellets as for other IR methods, so remain available for further analysis or future study.

FTIR-ATR analysis was undertaken using a Nicolet IS10 coupled with a Golden Gate Single Reflection Diamond ATR accessory. Spectra were recorded over the range 400-4000cm⁻¹, with an average of 64 scans per sample at 4cm⁻¹ resolution. Spectra were automatically baseline corrected using Thermo Scientific OMNIC software. References for inorganic compounds common in paints and pigments, including barium sulphate, magnesium sulphate, calcium sulphate, Prussian blue and talc were not measured directly for this study but taken from the literature (Vahur *et al.*, 2016)

7.3.3. X-Ray Fluorescence (XRF)

X-ray Fluorescence is a very useful technique for providing information regarding the elemental composition of a material (Hochleitner *et al.*, 2003; Mulholland *et al.*, 2017) (see chapter 5.2). As such, it can prove an important technique for identifying the types of materials which may be present in an object, even though it does not necessarily provide detailed information regarding the chemical structures. Limitations in using this technique should be noted. Firstly, XRF is often limited in detecting lighter elements (c. Z<11). This is in part due to a

secondary fluorescence mechanism common in lighter elements known as the auger process (Brouwer, 2010). In this mechanism, the X-ray emission is re-absorbed by the atom rather than emitted, resulting in further electron re-arrangements taking place and ultimately the emission of non-distinctive X-rays.

In addition, and problematic with historic samples, is the issue of interpreting exactly which part of a sample has been analysed when using XRF. The depth to which X-rays may penetrate a sample, and then from which fluorescent X-rays may escape and travel to reach a detector, is dependent upon the density of the sample and the position and quality of vacuum in which the detector is located. As such, sample interaction may only occur within the first fraction of a millimetre from the surface, and this should be borne in mind with historic samples which have not been powdered and thus homogenised. Lighter elements, moreover, typically emit photon with low energy, making it much harder for these to escape the sample and be detected, especially if analysis is not undertaken in a vacuum. For the above reasons care should be taken using any quantitative results provided by XRF analysis as they may omit the presence of lighter elements or not be representative of the bulk composition, and for this reason only the qualitative result as to the elements detected will be presented here.

Energy Dispersive XRF analysis was conducted using a PANalytical Omnia Epsilon 3 Unit with a Ag-tube X-ray source and SDDUltra detector. An excitation of 50kV was used in air.

7.3.4. X-Ray Diffraction (XRD)

XRD is a very powerful tool in identifying the presence of crystalline phases within historic materials, and can be useful for distinguishing between polymorphs (Corbeil, 2004; Debnath and Vaidya, 2006; Parras-Guijarro *et al.*, 2006). It has been used in conservation for this purpose, as well as in studies regarding the aging and deterioration of materials (see chapter 5.2). As with XRF, issues regarding the depth of interaction of X-rays with a non-homogenous sample should be borne in mind.

X-ray diffraction measurements were carried out with a PW3050/60 PANalytical X'PERT-PRO system with CuK α radiation. It was operated at 40kV, 40mA between a 2θ range of 5°-70° continuous scanning, with a step size of 0.0334°. XRD patterns were matched using the International Centre for Crystallography (ICDD) database.

7.3.5. Raman Spectroscopy

Raman spectroscopy is another technique widely used in conservation and functions due to the inelastic, Raman scattering of a monochromatic light source interacting with a sample (Edwards and Falk, 1997; Edwards *et al.*,

2006; Clark, 2007). In Raman scattering, a photon is absorbed by a molecule causing it to enter a higher virtual energy state for a short period. Eventually, the molecule will emit a photon to return to a lower energy state. A limitation of Raman Spectroscopy is that only a very small proportion of photons, approximately 1 in a million, are Raman scattered (Edwards and Chalmers, 2005). The majority undergo Rayleigh scattering in which the energy of the incident and scattered photon is the same. This can make detection of Raman scattered photons very difficult, as Rayleigh scattering can drown out their signal. Fluorescence can make this problem even more significant and is often encountered in historic samples, in which fluorescing of the material drowns out any signal from the relatively infrequent Raman scattered photons.

Raman spectra were acquired using a Renishaw inVia Confocal Raman microscope fitted with a CCD detector and samples were excited using a 785nm laser source with a maximum power of 75mW. The maximum laser power used was approximately 4mW to minimise sample degradation and fluorescence. Spectra were analysed with a 5x objective and spectra acquired in ranges between 100-2000 cm^{-1} . Quenching times of between a few minutes and several hours before measurements were tested to try and overcome fluorescence of samples. Spectra were base line corrected using Renishaw 4.1Wire software processing software.

7.4. Results

A summary of the materials identified in the aircraft fabric samples is provided here for ease of reference in Table 7-1.

Sample Source	Structure	Weave	Fabric Type	XRF	FTIR-ATR	XRD	Raman
Antoinette <i>Flight</i>	Clear base coat encapsulating fabric. Dark blue then lighter blue top coat of paint	Plain	Cotton	Ti, Ba, Zn, Pb	Cellulose Nitrate	Barite Zinc Oxide Gypsum Rutile	
Antoinette Technical File	Fabric substrate. No dope identified.	Plain	N/K		Magnesium Silicate		
Cierva C30a <i>Flight</i>	Red base coat impregnating fabric substrate Green top coat of paint	Plain	Linen	Fe, Ti	Cellulose Nitrate	Haematite Rutile Goethite	Iron oxide
Cody Bi-Plane Technical File	Clear base coat encapsulating fabric Yellow/cream top coat of paint	Plain	Linen	Ti, Fe, Ba	Cellulose Acetate Tri-phenyl Phosphate	Muscovite Goethite Barite Rutile	Titanium dioxide
JAP Harding Monoplane <i>Flight</i>	Clear base coat encapsulating fabric	Twill 4/1	Cotton		Cellulose Nitrate		
JAP Harding Monoplane Technical File	Clear base coat encapsulating fabric Brown surface coat	Plain	Cotton	Fe, Pb, Mn	Cellulose Acetate Tri-phenyl Phosphate Calcium Sulphate	Gypsum Barite Quartz	Lead carbonate Barium sulphate
Pterodactyl <i>Flight</i>	Red base coat impregnating fabric substrate Silver top surface	Plain	Cotton	Al, Fe	Cellulose Nitrate	Haematite Aluminium	Iron oxide
Roe Tri-Plane Technical File	Black layer over open weave fabric	Plain	N/K	Pb, S	Calcium Sulphate	Lead Carbonate Gypsum	
Se5a Fighter Plane Technical File	Clear base coat encapsulating lower fabric Red coating above fabric Silvery layer Brown paint layer	Plain	Linen	Al, Fe	Cellulose Nitrate	Haematite Aluminium Gypsum	
Supermarine S6B <i>Flight</i>	Red base layer encapsulating fabric Silvery layer Bright blue paint layer Dark blue paint layer	Plain	Linen	Zn, Fe	Cellulose Nitrate Prussian Blue	Prussian Blue Haematite Barite Zinc Oxide Gypsum	
Vickers Vimy <i>Flight</i>	Clear base coat encapsulating fabric Yellow/cream top coat of paint	Plain	Linen	Ti, Ba	Cellulose Acetate Tri-phenyl Phosphate	Muscovite Barite Zinc Oxide Rutile	Titanium dioxide
Vickers Vimy Technical File	Clear base coat encapsulating fabric	Plain	Linen		Cellulose Acetate Tri-phenyl Phosphate		

Table 7-1: Summary of compounds and materials identified in the construction of the doped-fabrics from the Science Museum technical files and aircraft currently on display in *Flight*

7.4.1. Visual Inspection and Microscopy

Fabric Structure

An inspection of the aircraft fabrics taken from both the technical file and gallery shows that they are nearly all composed of a densely woven fabric. The exception to this is the Roe Tri-plane material technical file, where the substrate is a loose, open weave netting, which has then been covered with a thin paper or similar material.

For fabrics made of a close weave, all but one are a plain weave, typical examples of which can be seen in Figure 7-1 in the Vickers Vimy sample taken from *Flight* and the Vickers Vimy and JAP Monoplane technical file samples. Only the JAP Monoplane *Flight* sample was not made using a plain weave, but was instead a type of 4/1 twill in which a yarn crosses over four yarns in the normal direction before passing under one.

Although not made of different weaves, a visual comparison of the Vickers Vimy technical file and gallery samples also indicates potential differences between the fabric structures. The gallery sample appears to have a denser weave in which the yarns are all closely packed together with relatively few, small gaps appearing between the interstices compared to the technical file material where most of the interstices appear open.

Inspection of the reverse side of the Vickers Vimy technical file material, however, shows that these interstices are not open but filled with a coating material, and this was also observed on the JAP Harding Monoplane technical file sample where small particulate matter was trapped in a film filling the interstices.

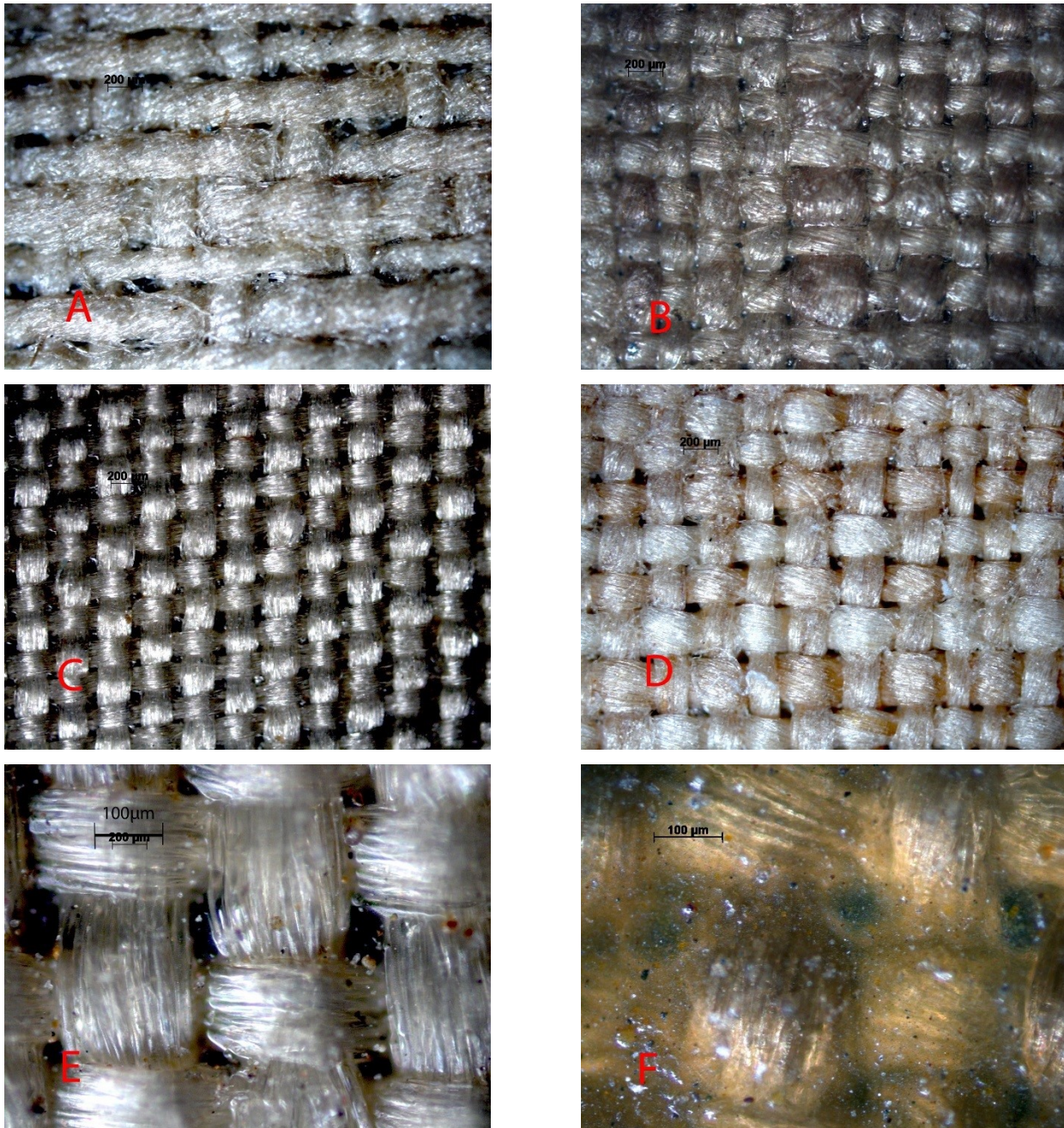


Figure 7-1 Reflected light images of doped-fabrics. From top left to right; (A) JAP Monoplane gallery, (B) Vickers Vimy gallery sample, (C) JAP technical file material, (D) Vickers Vimy technical file material, (E) JAP technical file reverse side and (F) Vickers Vimy technical file reverse side.

The cross sections of samples taken from technical files and aircraft on display in *Flight* are shown in Figure 7-2 and Figure 7-3 respectively. In all cases the yarn ends have remained clustered together on cutting, rather than separating into individual fibres, a similar behaviour to that observed in modern fabrics after doping (see chapter 8.3.1)

Of the technical file samples, the Antoinette monoplane, JAP Monoplane and Vickers Vimy do not have paint layers or pigmented dopes impregnating the fabric. Only one technical file sample, that of the Se5a, has a red base coat though this does not appear to penetrate throughout the material, but sits largely on top of the fabric substrate suggesting the potential presence of a further clear coat beneath. The Se5a red coat is overlaid by a thin silver coat, and then an even thinner brown top coat. In the case of the Cody Bi-Plane there is a cream coloured layer directly over what appears to be an unpigmented fabric substrate.

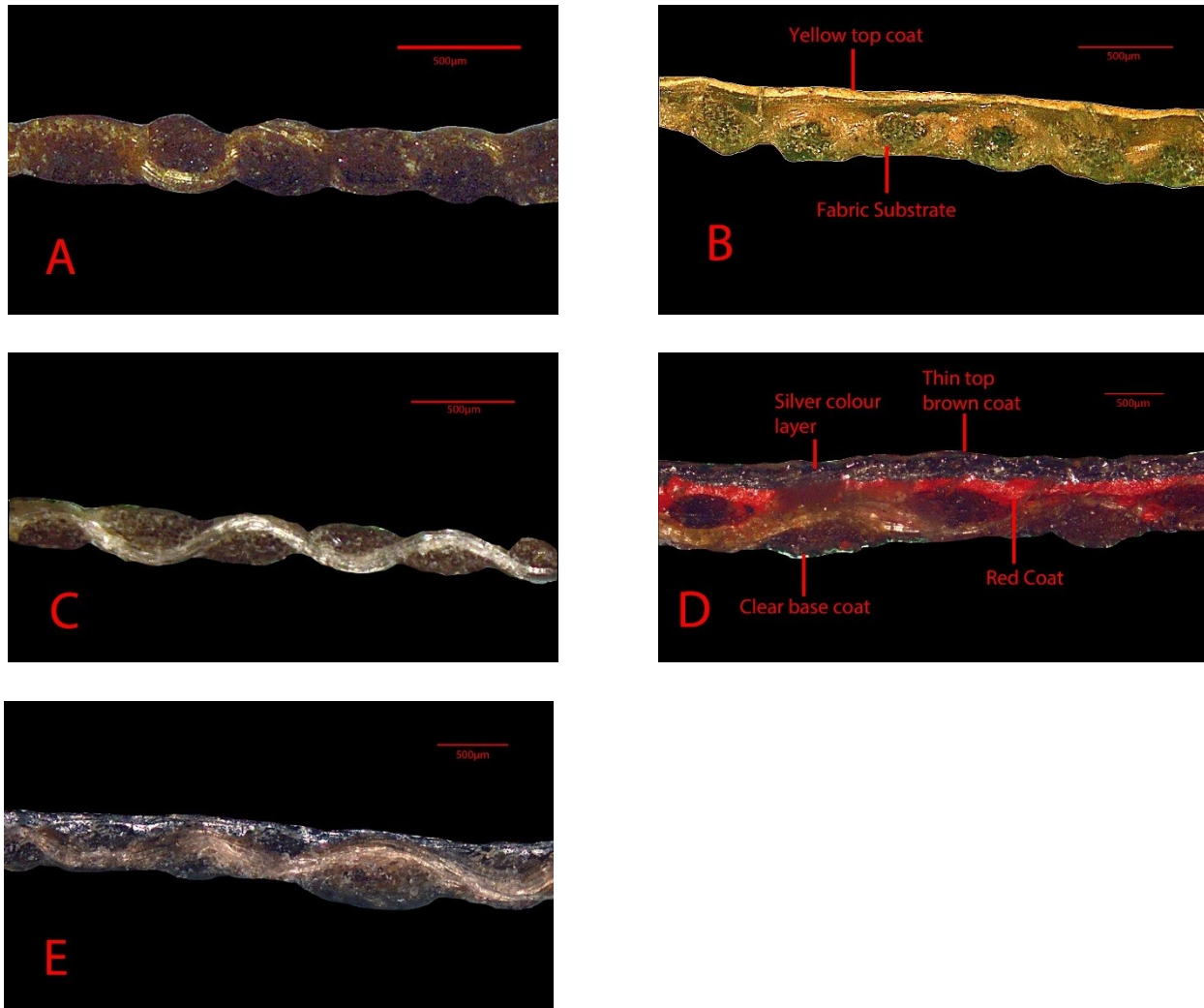


Figure 7-2 Reflected light cross sections of doped-fabric samples from the technical files. From top left to right; (A) Antoinette Monoplane, (B) Cody Bi-Plane, (C) JAP Monoplane, (D) Se5a Fighter and (E) Vickers Vimy.

Among the gallery samples only the JAP Monoplane does not have any layers of paint or coloured dopes. Three of the gallery samples, the Cierva C30a, Pterodactyl and Supermarine S6B have been treated with a red base coat which penetrates throughout the fabric substrate. Above the red coat of the Cierva C30a, there is a final

green layer, but in the case of the Pterodactyl and Supermarine there is a silver coloured coating above, as found on the Se5a. This silver coloured layer forms the top coat of the Pterodactyl whilst in the case of the Supermarine, two further layers are visible, a bright blue layer underneath a darker top one.

In the case of the Vickers Vimy gallery sample there appears to be a thin cream/yellow layer directly over a clear base coat impregnating the fabric, without any use of red or silver coloured underlayers. In the sample of the Antoinette Monoplane sample, the top surface is a blue paint layer, which may then be underlaid with a slightly darker, almost purple looking layer beneath, and the fabric ends do not appear pigmented.

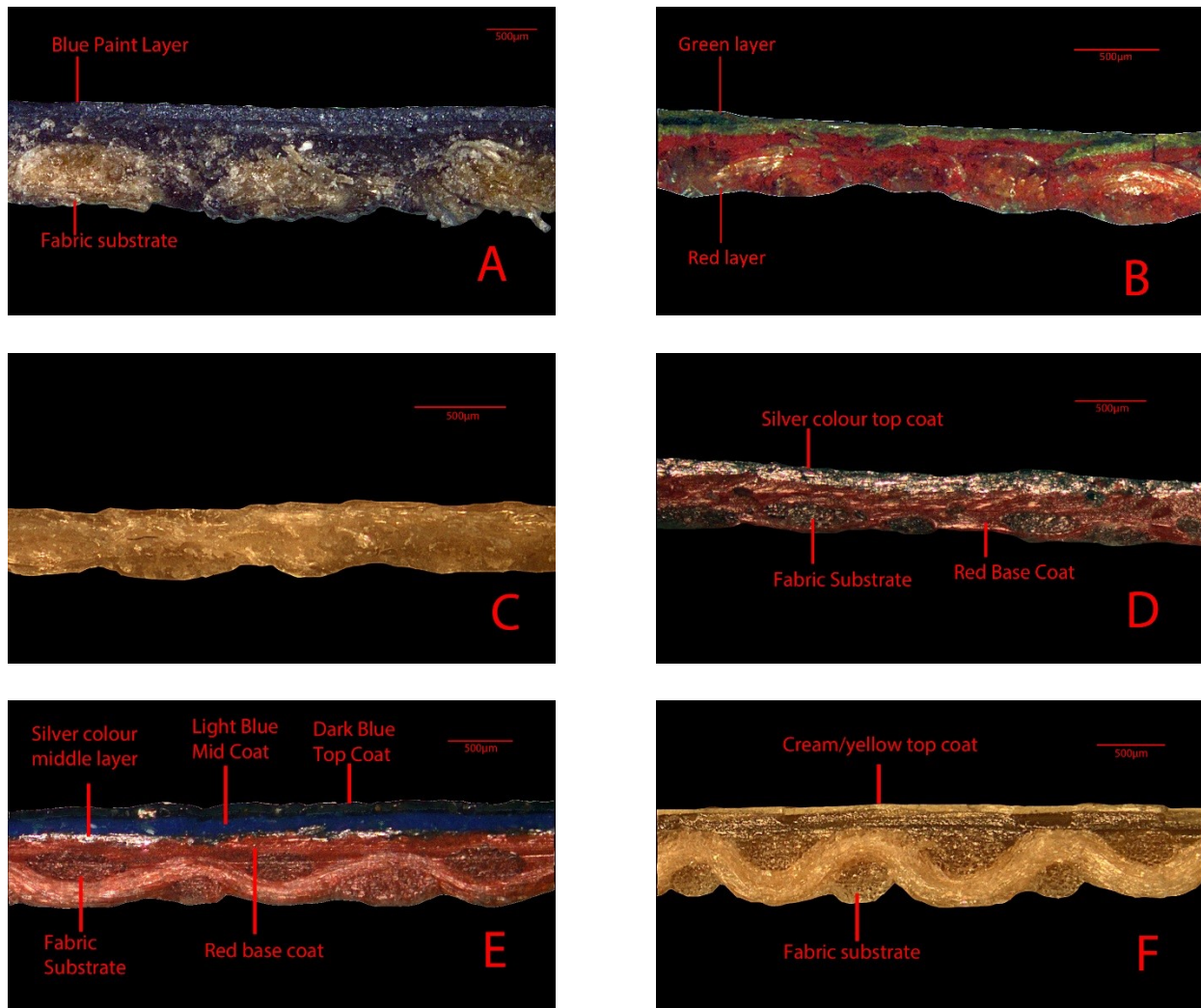


Figure 7-3 Reflected light cross sections of fabric sampled from aircraft displayed on *Flight*. From top left to right (A) Antoinette Monoplane, (B) Cierva C30a, (C) JAP Monoplane, (D) Pterodactyl, (E) Supermarine S6B and (F) Vickers Vimy

Fibre Identification

Micrographs of fibres from the 9F1 Irish Linen and 7F8 cotton, both un-doped and having been doped with A9701 butyrate dope, are provided in Figure 7-4.

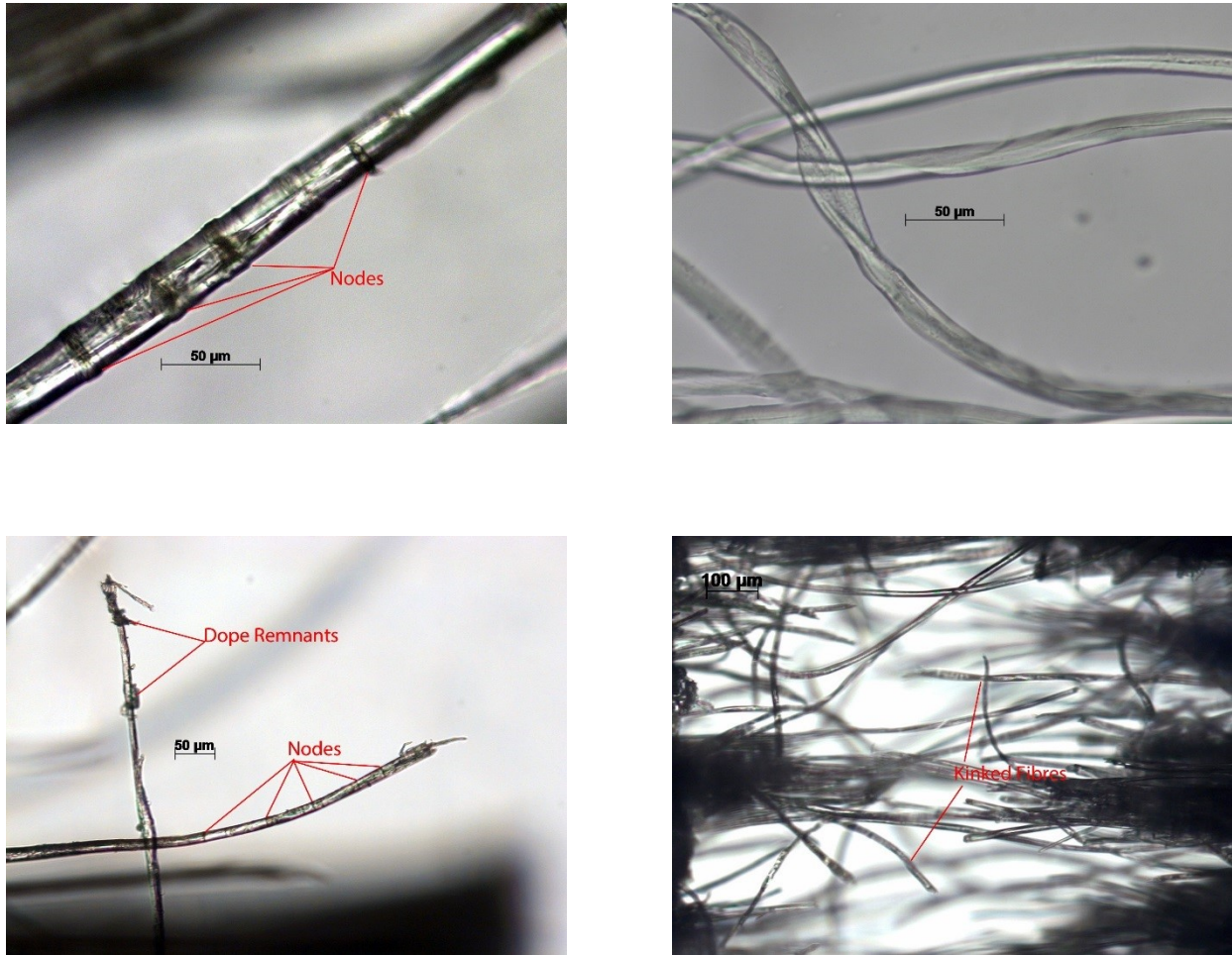


Figure 7-4 Bright field images of fibres. From top left to right, a fibre from 9F1 Irish Linen, a fibre from the 7F8 Cotton, fibres of 9F1 Irish linen doped with Randolph 9701 Butyrate after tensile testing and fibres from 7F8 Cotton doped with Randolph 9701 Butyrate after tensile testing

Flax fibres used in making linen are straight and have distinctive ‘bamboo’ nodes or dislocations along their length. The cause of these dislocations is not certain, though studies indicate they are important in influencing its material properties, creating chemically active sites where dyes, enzymes and other compounds preferentially react, but also points of weakness where failure under loading is more likely to occur (Akin, 2013).

Cotton fibres do not have these distinctive nodes but are characterised by having several ‘kinks’ along their length, creating a twisted, ribbon like structure. This structure occurs after the cotton boal containing the seeds

bursts, allowing moisture to evaporate from the lumen at the centre of the fibres. As the moisture evaporates, the fibre structure collapses on itself, and random kinks then occur due to the twisting of cellulose fibrils making up the primary and secondary walls around the lumen (Mather R. R. and Wardman, 2011).

The identification of these diagnostic features in doped materials was more difficult as individual fibres could not be isolated. Tensile testing was found to pull some fibres out of the dope matrix which could be imaged, though the morphological features were still largely obscured due to dope remnants clinging to the fibres.

Technical File

Micrographs of fibres from aircraft fabrics found in the technical files are shown in Figure 7-5. Straight fibres with dislocations characteristic of flax are visible in the micrographs for the Cody Bi-plane, Se5a Fighter and Vickers Vimy. Such dislocations were not noted on fibres of the JAP Monoplane, though distorted fibres such as are found in cotton fibres were noted. It was not possible to identify the Antoinette Monoplane or Roe Tri-Plane fabrics as fibres could not be adequately separated for analysis.

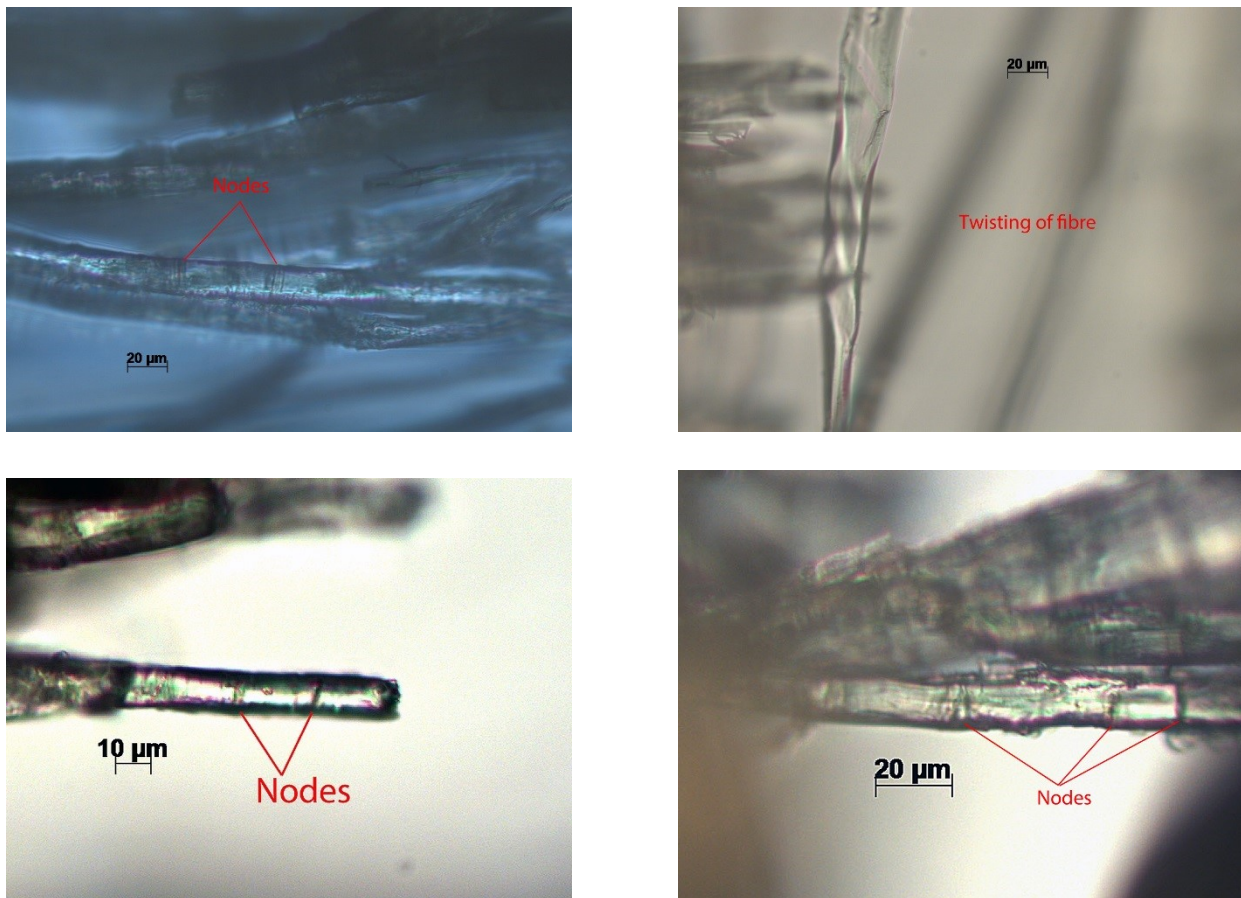


Figure 7-5: Bright field images of fibres from the technical files after tensile testing. From top left to right the Cody Bi-Plane, JAP Harding Monoplane, the Se5a aircraft and Vickers Vimy

Gallery Samples

Micrographs of fibres from aircraft fabrics sampled from *Flight* are shown in Figure 7-6. The fibres of the Cierva C30a, Supermarine S6B and Vickers Vimy contain features characteristic of linen fibres, including straight fibres and bamboo nodules. The fibres of the JAP monoplane and Pterodactyl in contrast are ribbon like and contorted such as are expected of cotton fibres. It was not possible to identify the Antoinette Monoplane fibre type as individual fibres could not be adequately separated.

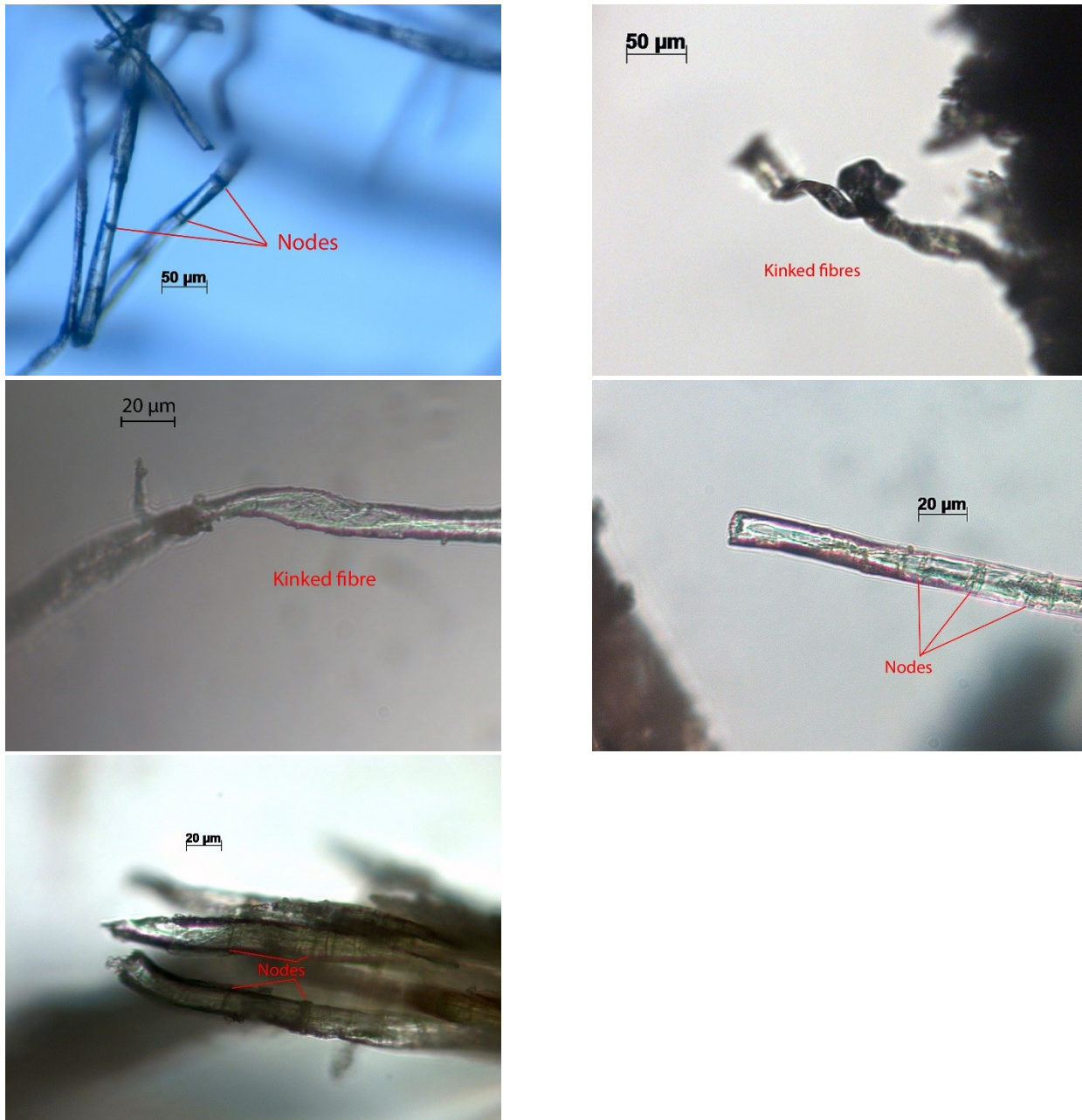


Figure 7-6 Bright field images of fibres from the gallery sample after tensile testing. From top left to right the Cierva C30a, JAP Monoplane, Pterodactyl, Supermarine S6b and Vickers Vimy

7.4.2. FTIR-ATR Results

References

The FTIR-ATR spectra of modern materials used in constructing doped-fabric aircraft are shown in Figure 7-7. For 9F1 Irish linen fabric and the 7F8 aircraft cotton bands in the 1000-1200cm⁻¹ region are attributable to different vibrations of the pyranose rings which form the cellulose chain (Garside and Wyeth, 2003).

The FTIR-ATR spectra of the Randolph A9701 Tautening Butyrate Dope, Randolph 210 Nitrate Dope and Red Neogene Dope contain three peaks attributable to cellulose nitrate at 1650, 1280 and 840cm⁻¹ (Quye *et al.*, 2011; Berthumeyrie *et al.*, 2014), whilst the spectrum of the Randolph A9701 Butyrate Dope has strong, diagnostic bands around 1170 and 1235cm⁻¹, which can be attributed to stretching of the butyryl and acetyl substituent groups respectively (Saunders and Taylor, 1990). The strong band at 1740cm⁻¹ is the result of carbonyl groups in the acetate and butyrate substitute groups. A summary of IR bands for cellulose, cellulose nitrate and cellulose acetate butyrate has been provided in Table 7-2.

The Randolph A9701 Butyrate dope spectrum also has bands at 1650, 1280 and 840cm⁻¹, attributable to cellulose nitrate. This indicates that the Randolph butyrate dope is not a pure product, but a mixture of the two cellulose esters. There are no bands at 1170 or 1235cm⁻¹ associated with cellulose acetate or cellulose acetate butyrate in the Randolph 210 Nitrate Dope and Red Neogene Dope, indicating these are not a mix of cellulose esters.

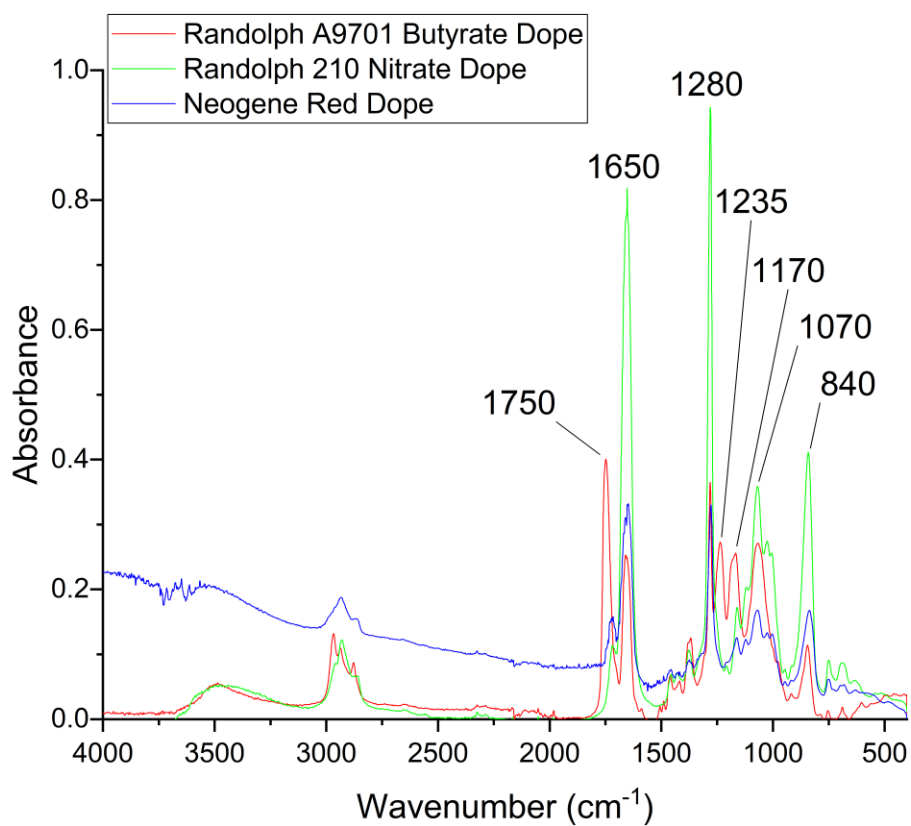
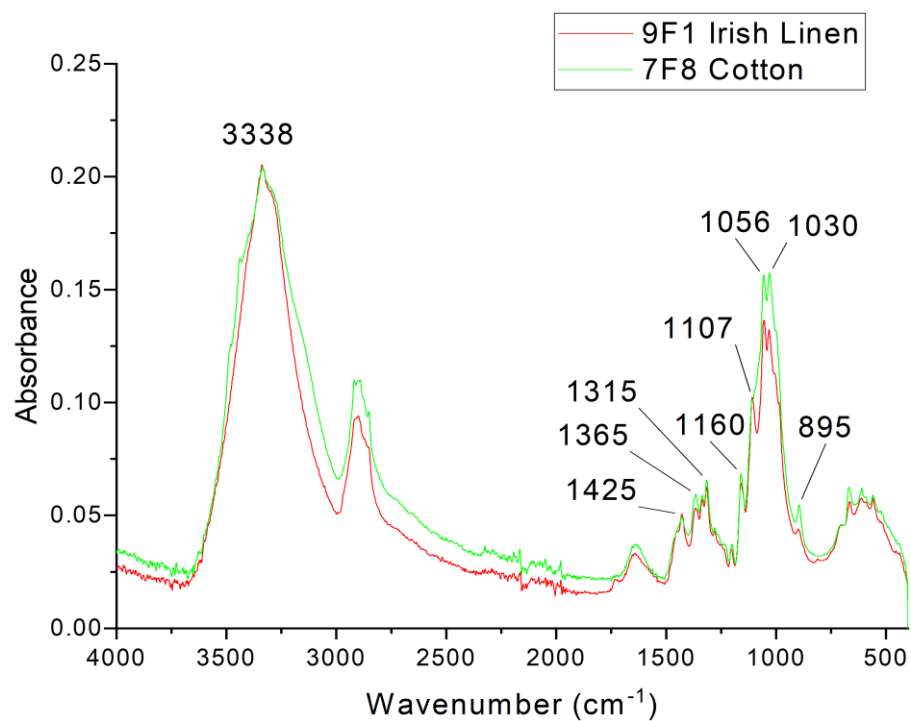


Figure 7-7 FTIR-ATR spectra of modern reference materials used in constructing doped-fabric aircraft. Top 7F8 cotton and 9F1-irish linen. Bottom commercially available aircraft dopes.

Cellulose ¹			Cellulose Nitrate ²			Cellulose Acetate Butyrate ³		
Wave number (cm ⁻¹)	Assignment	Note	Wave number (cm ⁻¹)	Assignment	Note	Wave number (cm ⁻¹)	Assignment	Note
3335	v(OH)	Free	3500	v(OH)		3500	v(OH)	
2900	v(CH)		2960	v _{as} (CH ₂)		2968	v _{as} (CH ₂)	
2850	v _s (CH ₂)		2930	v _s (CH ₂)		2935	v _s (CH ₂)	
1734	v(C=O)	Ester	1650	v _{as} (NO ₂)		1747	v(C=O)	
1635		Adsorbed water	1415	δ(CH ₂)		1415	δ(CH ₂)	
1595	v(C=C)	Aromatic in plane	1460			1460		
			1375	δ(CH)		1380	δ(CH)	
1455	δ(CH); δ(C-OH)	Primary and secondary alcohols	1280	v _s (NO ₂)		1365	δ(CH)	
1425	δ(CH)		1160	v _{as} (C ₅ OC ₁ OC ₄)	Acetal structure	1235	v _{as} (COC)	Linkage of acetate groups
1365	δ(CH)		1121	v _s (C ₅ OC ₁ OC ₄)	Acetal structure	1176	v _{as} (COC)	Linkage of butyrate groups
1335	δ(CH ₂)	Wagging	1068	v(C ₁ OC ₄)	Acetal structure	1065	v(C ₁ OC ₄)	Acetal Structure
1315	δ(CH)		840	v(NO ₂)				
1200	δ(COH); δ(CCH)		752	δ(NO ₂)				
1157	v _{as} (CC)	Ring breathing	688	δ(NO ₂)				
1107	v(COC)	Glycosidic bond						
1055	v(COH)	Secondary alcohol						
1025	v(COH)	Primary alcohol						
895	v _s (COC)	In plane						

Table 7-2: Infra-Red band assignments for three common components of a doped-fabric aircraft; cellulose, cellulose nitrate and cellulose acetate butyrate. Wavenumbers are based on reference spectra obtained from 9F1 Irish linen, A9701 Randolph Butyrate dope and Randolph 210 Nitrate dope. (Assignments are adapted from the literature, ¹Garside and Wyeth (2003), ²Quye et al. (2011), ²Berthumeyrie et al (2014), and ³Saunders and Taylor (1990))

A spectrum of tri-phenyl phosphate, a common plasticiser according to literature sources, was also acquired (Figure 7-8). Peaks around 1588 and 1487 cm⁻¹ are attributable to the C=C bonds in the aromatic rings, and the

peaks at 690 and doublet around 767 cm^{-1} are characteristic of out of plane bending of a mono-substituted aromatic ring. The strong bands at 1184 and 955 cm^{-1} are the result of P=O and P-O-C bonds respectively (Lampman *et al.*, 2010).

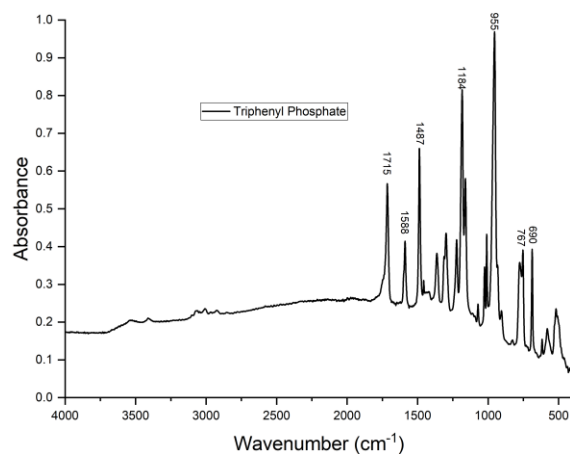


Figure 7-8: FTIR-ATR spectrum of triphenyl phosphate

Technical File

Cellulose nitrate was detected on only one technical file sample, that taken from the Se5a aircraft. This spectrum does not appear to have a cellulose acetate or cellulose acetate butyrate component or peaks associated with any additives. Three of the other aircraft samples from the technical files, those from the Vickers Vimy, JAP Monoplane and Cody Bi-Plane have strong absorption bands around 1230 and 1050 cm^{-1} , indicative of a cellulose acetate dope (Figure 7-9). There is not a strong band around 1170 cm^{-1} , however, indicating there is little or no butyrate content. No peaks associated with cellulose nitrate were found in any of the spectra for the Vickers Vimy, JAP Monoplane or Cody Bi-Plane.

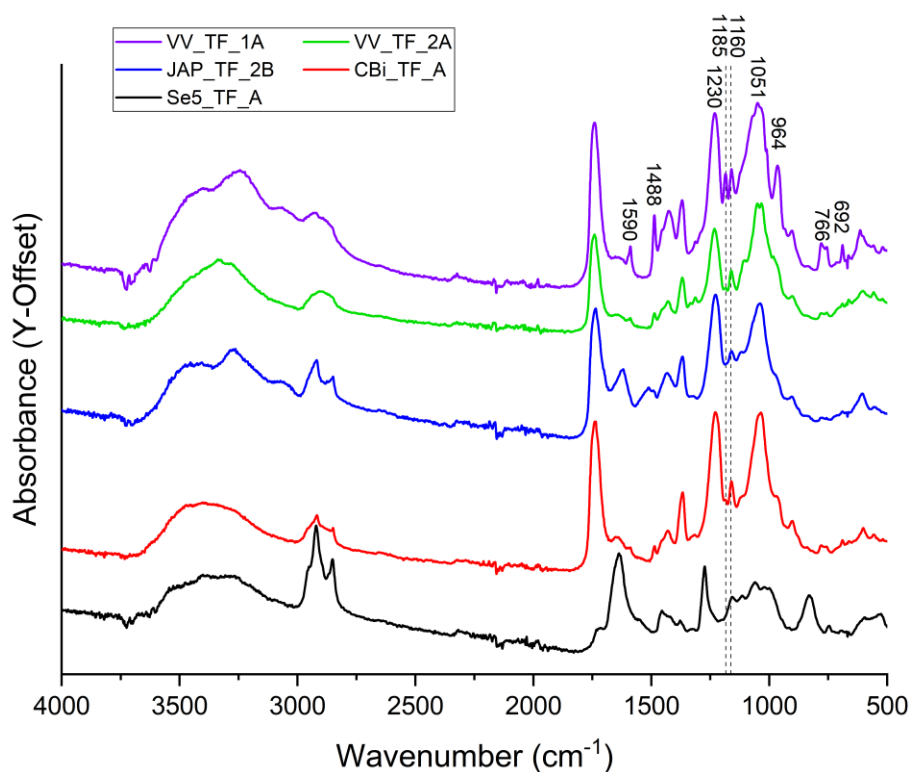


Figure 7-9: FTIR-ATR spectra of technical file fabric samples on which cellulose acetate or cellulose nitrate were detected.

Further bands in the spectrum of the Vickers Vimy, include a doublet around 760cm^{-1} , a strong peak around 965cm^{-1} and further ones at 1185 , 1490 , 1590 and 1684cm^{-1} which indicate the presence of the plasticiser tri-phenyl phosphate. These bands are also present in the spectrum of the Cody Bi-plane although are much weaker than seen in the Vickers Vimy samples, and are not detectable in the spectra of the JAP monoplane. The samples taken from the second Vickers Vimy envelope, pieces 2-4, also all had spectra containing similar peaks, indicating a cellulose acetate dope with triphenyl phosphate plasticiser.

The spectrum of the Cody Bi-Plane paint exterior had peaks at 604 , 983 , 1065 , 1107 and 1187cm^{-1} (Figure 7-10). Sulphates typically have strong absorption bands in the $1000\text{-}1200\text{cm}^{-1}$ range, and the three peak pattern of the Cody Bi-plane spectrum is attributable to barium sulphate (Boselli *et al.*, 2009; Vahur *et al.*, 2016). The interior of the Cody Bi-plane paint sample also had peaks associated with cellulose acetate and tri-phenyl phosphate, comparable to the spectra of the fabric surface studied where the paint surface had been lost. This indicates that the paint surface may have adhered to the dope and peeled off some of the coating when it separated.

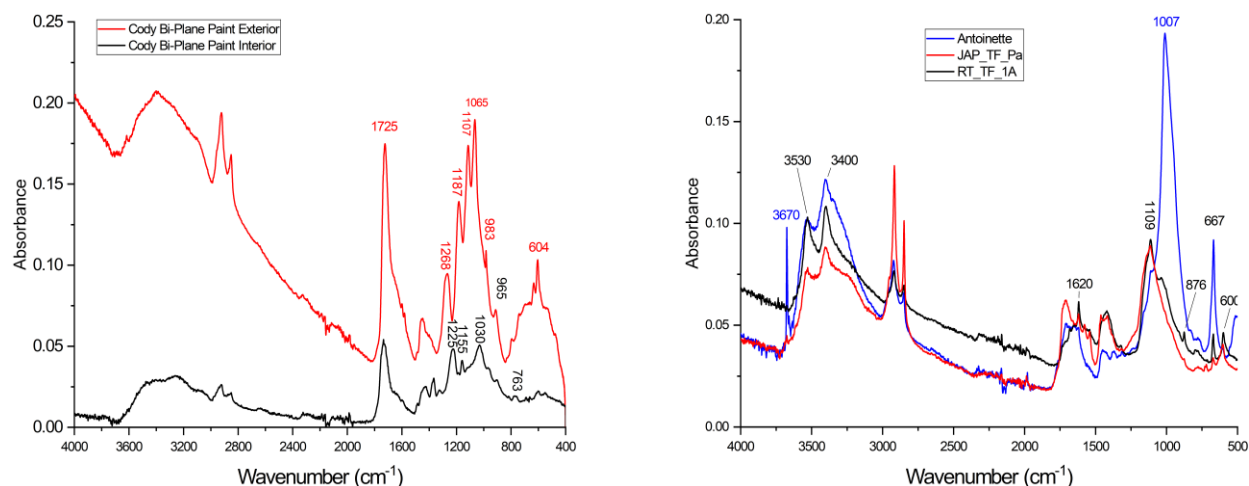


Figure 7-10: Left, FTIR-ATR spectra from the Cody Bi-Plane paint found in the technical file. Right, FTIR-ATR spectra from technical file material found for the Antoinette Monoplane, Roe Tri-Plane and JAP Monoplane coating

Analysis of Roe Tri-plane material did not identify materials attributable to nitrate or acetate dopes. In the spectrum of the Roe Tri-plane there was a strong peak at 1109 and further ones at 1620, 876, 671 and 599 cm^{-1} . A similar spectrum was obtained from analysis of the separated piece of coating from the JAP Monoplane, sample JAP_TF_Pa, and, in both cases, the spectra may be attributed to calcium sulphate (Liu, Wang and Freeman, 2009).

The Antoinette sample had a strong peak near 1010 cm^{-1} , as well as further ones at 667 and 3670 cm^{-1} . This is attributable to hydrated magnesium silicate ($\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$), more commonly known as talc (Parry *et al.*, 2007; Vahur *et al.*, 2016). The single sharp peak at 3670 is particularly distinctive, and is attributed to hydroxyl groups bonding to magnesium. No peaks for rubber or any other type of dope were detected, despite a hand written note on the sample describing it as rubberised.

Gallery Samples

The interior surfaces of five gallery samples, those from the Antoinette Monoplane, Cierva C30a, Pterodactyl, JAP monoplane and Supermarine S6b interior had peaks characteristic of cellulose nitrate (Figure 7-11), though in the case of the Cierva C30a, JAP Monoplane and Supermarine S6B these bands are relatively weak as strong bands more typical of cellulose, presumably from the fabric substrate, are also strong.

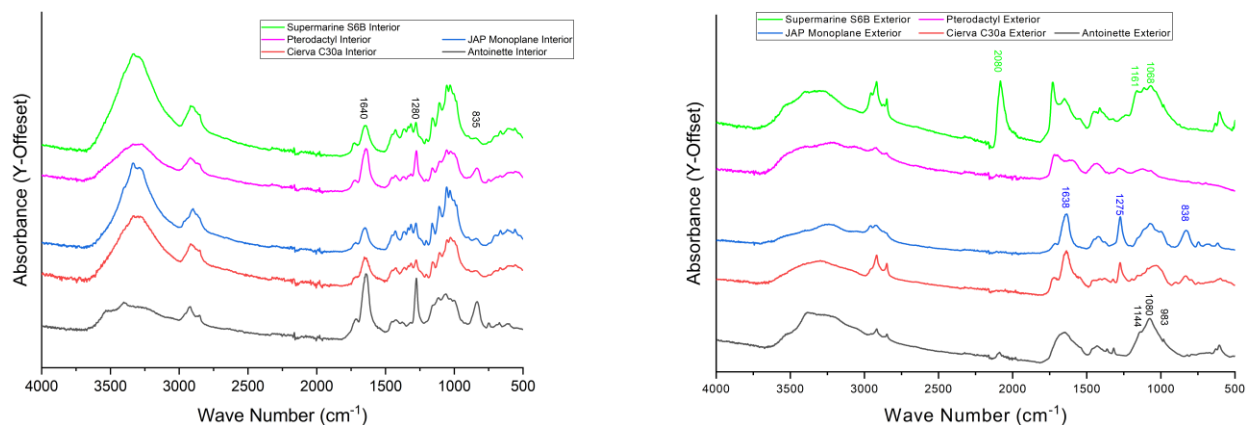


Figure 7-11 FTIR-ATR spectra of aircraft fabrics from aircraft on display in *Flight* in which Cellulose Nitrate was detected. The aircraft are the Antoinette Monoplane, Cierva C30a, JAP Harding Monoplane, Pterodactyl and Supermarine S6B. Left the interior surface, right the exterior surface

Cellulose nitrate bands are not discernible in the spectra from the exterior fabric surfaces of the Pterodactyl, Antoinette Monoplane or Supermarine S6B, but are strong on the Cierva C30a and JAP Monoplane. In the case of the Antoinette Monoplane and Supermarine the presence of bands potentially attributable to sulphate containing compounds are present in the $1000\text{--}1200\text{cm}^{-1}$ region, and a strong band at 2080cm^{-1} on the Supermarine S6B is also evident, which is attributable to the pigment Prussian blue (Learner, 1998; Vahur *et al.*, 2016).

The interior fabric surface and exterior painted surface of the Vickers Vimy fabric did not detect any signals from a dope compound (Figure 7-12). The spectra are instead dominated by the pattern typically expected of a cellulosic textile for the fabric interior and barium sulphate on the painted exterior.

After the Cody Bi-plane example in which some of the dope appeared to have peeled off with the paint, it was decided to remove a small area of paint and analyse the two new surfaces revealed. The spectrum of the paint interior contained peaks attributable to cellulose acetate combined with tri-phenyl phosphate, whilst that of the fabric substrate directly below the painted area removed was that of cellulose, and comparable to the spectrum of the inner fabric surface. This lends further support to the finding of the Cody Bi-plane that loss of the paint layer can strip off the dope film with it.

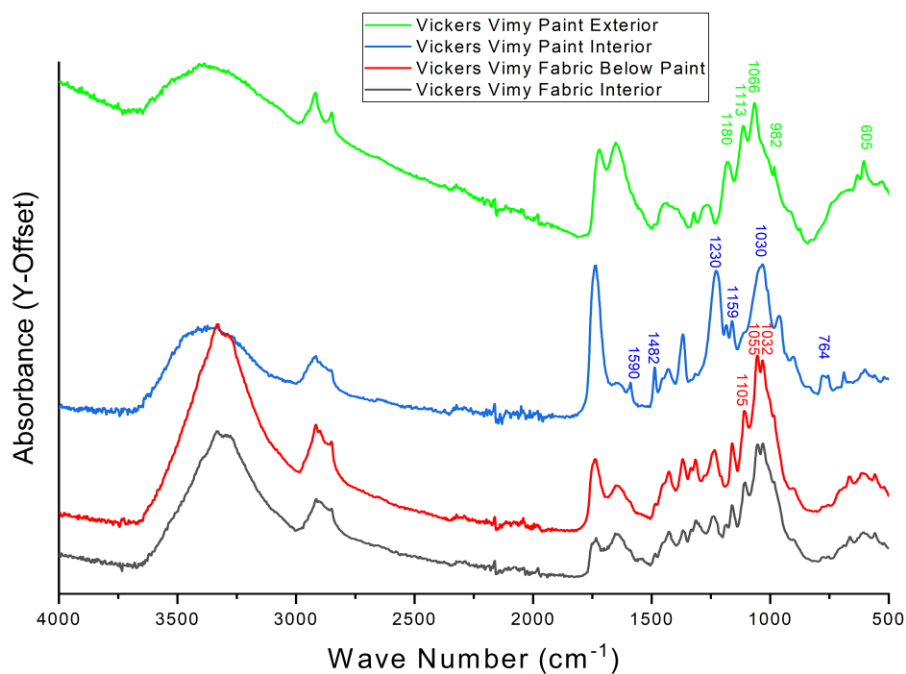


Figure 7-12 FTIR-ATR spectra of the different surfaces of the Vickers Vimy fabric and paint

7.4.3.XRF Results

Technical File

The XRF spectra of samples taken from the technical files is presented in Figure 7-13. On all samples elements due to potential surface contamination, such as chlorine, calcium and potassium were detected. These could have been introduced by various processes such as the accumulation of dirt, the transfer of salts from handling or atmospheric pollution.

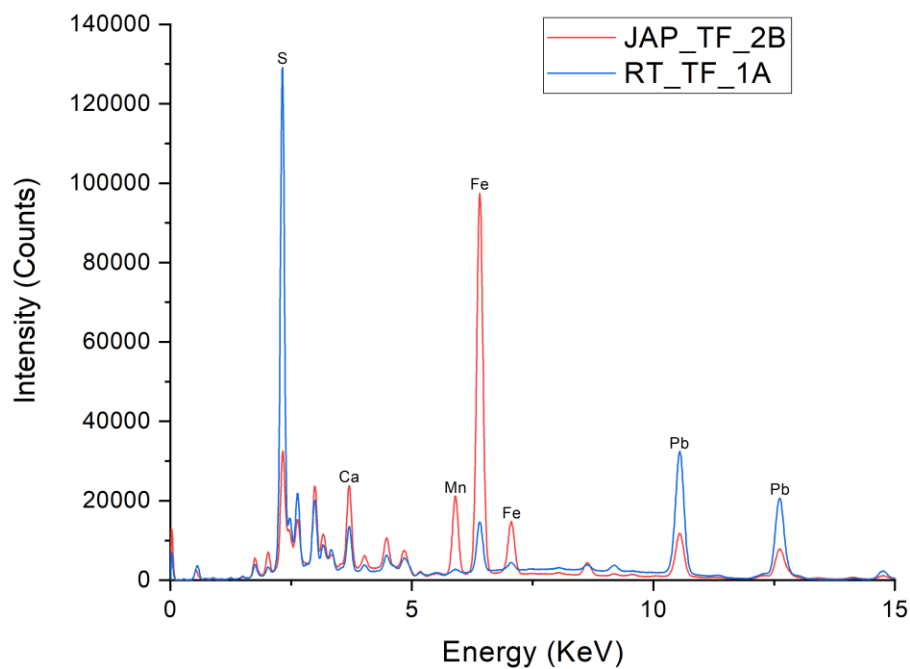
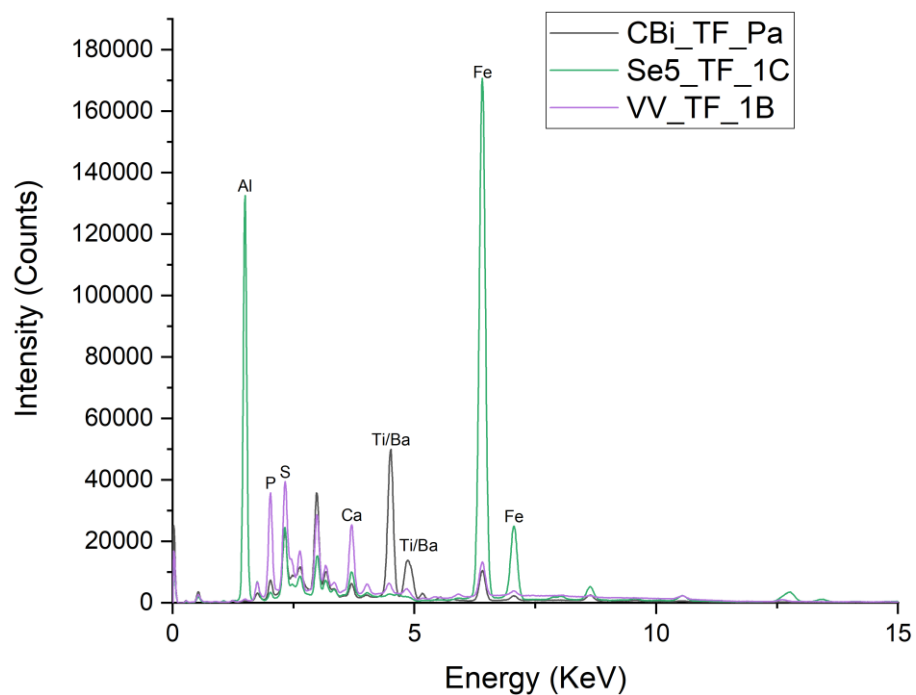


Figure 7-13: XRF spectra of material taken from the technical file samples. Top; non lead containing samples. Bottom lead containing samples

The paint sample from the Cody Bi-Plane had a strong signal for titanium, and was also found to contain iron, and barium. Only one technical file sample, the presumed exterior surface of the Se5a, had a very high signal for aluminium, as well as high levels of iron.

Samples taken from the JAP monoplane indicated high levels of iron containing compounds, and the presence of manganese and lead were also detected. The only other aircraft with significant lead signals was that of the Roe Tri-plane, and this sample also had a very large sulphur content.

Gallery Samples

The XRF spectra of gallery samples is provided in Figure 7-14. As with the technical file samples most samples measured concentrations of potential contamination elements and, in the case of the JAP Harding Monoplane no other notable elements were detected.

The Pterodactyl exterior surface recorded a strong signal for aluminium whilst on the interior, almost no aluminium was detected but a very strong signal for iron. High levels of iron were also measured on the interior surface of the Cierva C30a, as well as its paint and exterior fabric surface. Zinc was detected in the Antoinette Monoplane sample and the Supermarine S6B samples. Also detected in the monoplane sample were barium and lead. Strong signals for titanium were detected on the paint surface of the Vickers Vimy, as well as smaller ones on the Cierva C30a and Antoinette Monoplane.

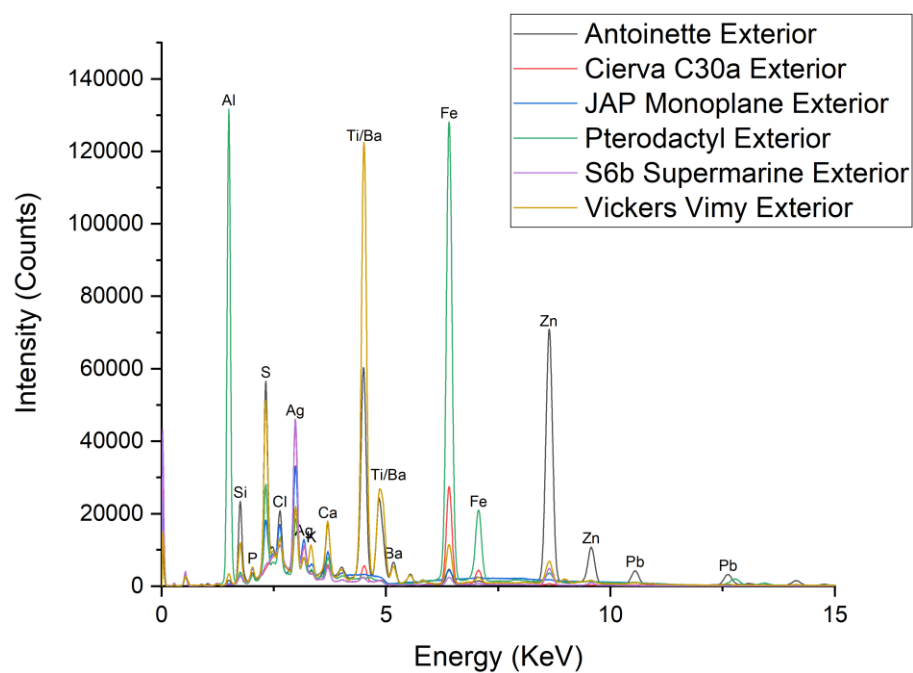
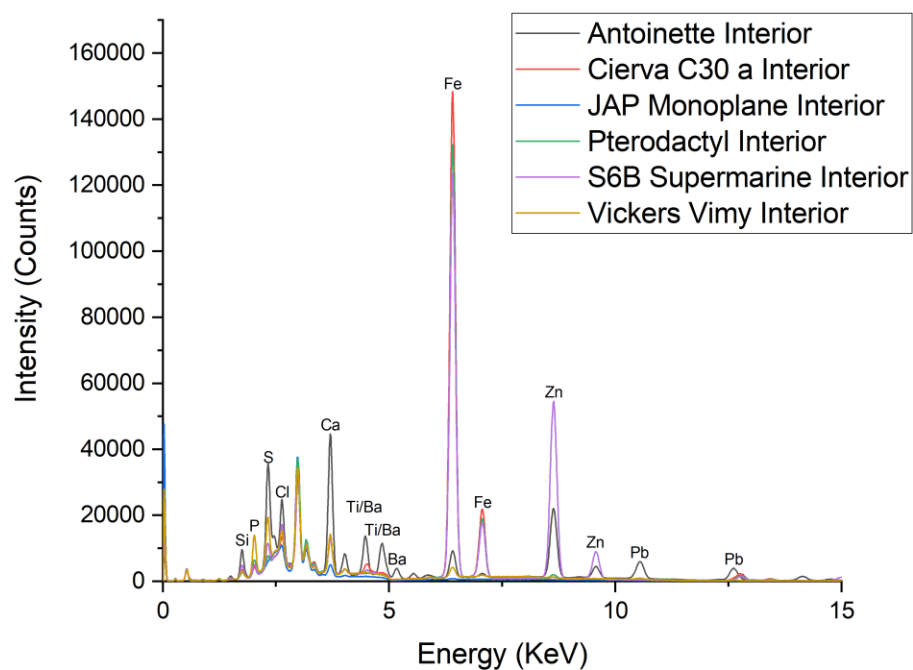


Figure 7-14: XRF spectra of samples from aircraft on display in *Flight* at the Science Museum. Top interior surfaces and bottom exterior surfaces.

7.4.4.XRD Results

Reference Materials

The XRD patterns of the reference material contained strong peaks associated with cellulose as is to be expected given that they are all composed of cellulose and its derivatives (Figure 7-15). The very broad nature of the peaks in the dope films, especially compared to the fabrics is notable indicating these have a low degree of crystallinity. The only material in which an additional pattern was detected was the Red Neogene dope, in which haematite was detected, as was expected for this dope formulation.

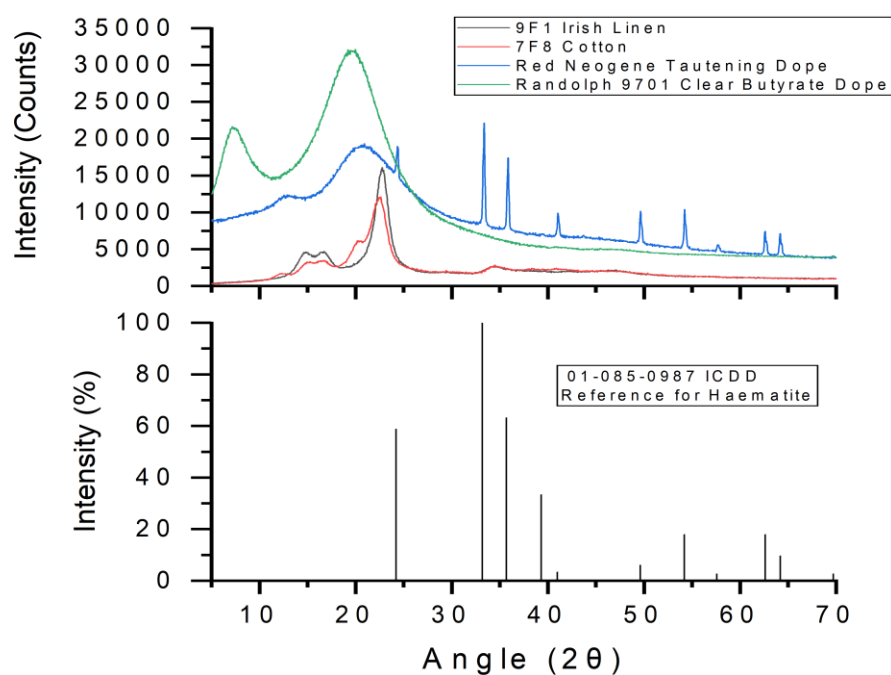


Figure 7-15: Top, XRD pattern of modern reference materials used in constructing doped-fabric aircraft. Below ICDD reference pattern 01-085-0987 for Haematite.

Technical File Samples

The XRD patterns of aircraft sampled from the technical files are provided in Figure 7-16. The simplest XRD pattern obtained from technical file samples were those of the Vickers Vimy, in which the main feature is the broad peaks typical of a cellulosic fabric, and smaller peaks due to gypsum and quartz. Also relatively straightforward were the XRD pattern of the Se5a sample, the compounds identified comprising haematite, aluminium and gypsum. Variation was noted depending on the side of the Se5a samples analysed, the signal for

aluminium being much stronger on the surface with the shiny coating, which has been assumed to have been the exterior.

Compounds identified in the external paint layer of the Cody Bi-Plane included muscovite (mica), goethite (brown ochre), barite (barium sulphate) and rutile (titanium dioxide) which are all common additives in paints as fillers and pigments. Analysis of the JAP Monoplane paint fragment identified gypsum, barite and goethite.

The XRD pattern of the Roe Tri-plane is dominated by that of synthetic hydrocerussite (basic lead carbonate), the mineral used in making white lead which was a common compound for white pigments in early paints. Also detected was gypsum.

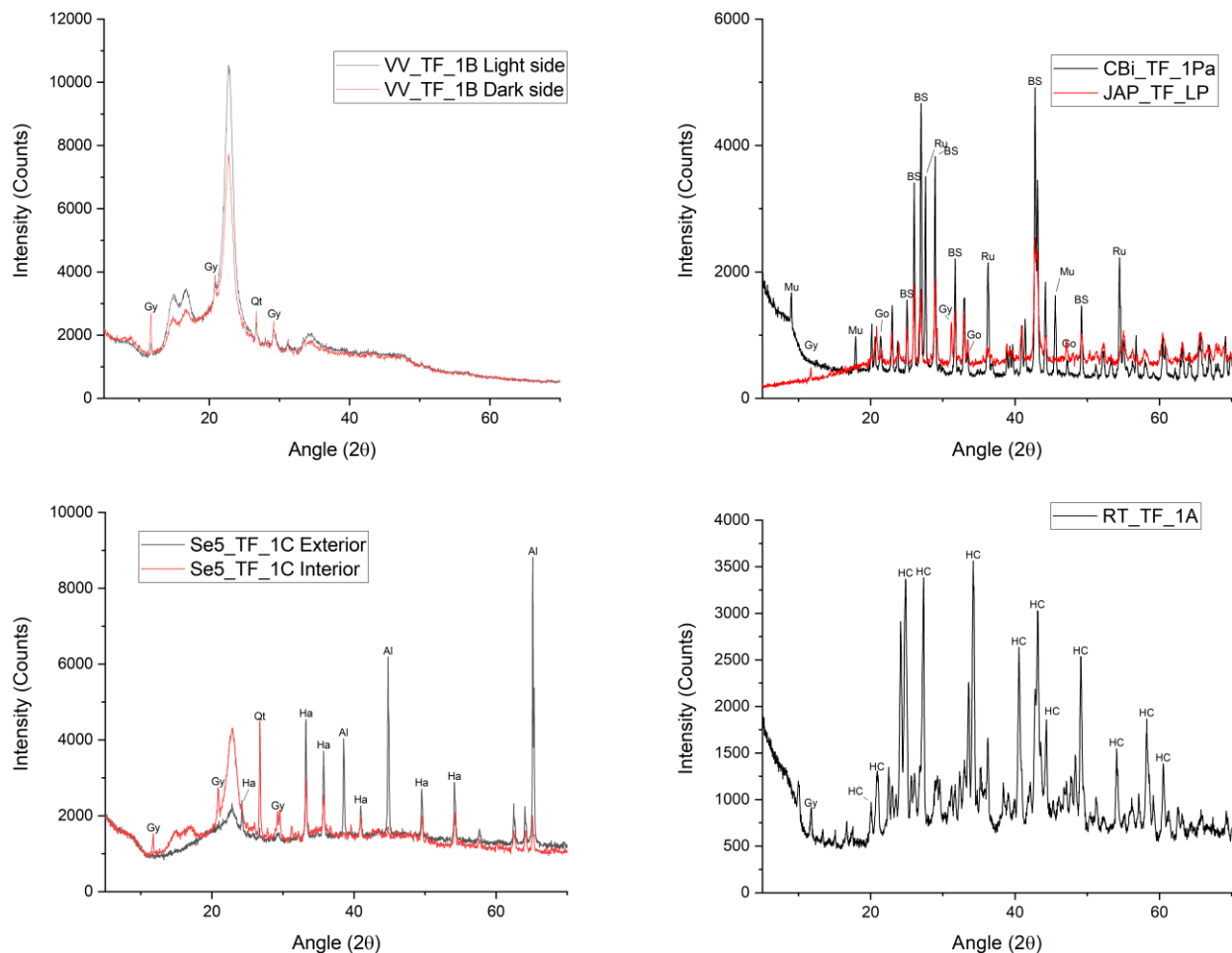


Figure 7-16: XRD patterns of samples taken from the technical files of doped-fabric aircraft at the Science Museum. Gy = gypsum, Qt = quartz, Mu = muscovite, Go = goethite, BS = barium sulphate, Ru = rutile, Al = aluminium, Ha = Haematite, HC = hydrocerussite

Gallery Samples

In the case of the samples taken from display in *Flight* the simplest XRD patterns were both surfaces of the JAP Monoplane and the interior side of the Vickers Vimy where the only feature of note are the peaks as observed in samples of a cellulose dope or textile.

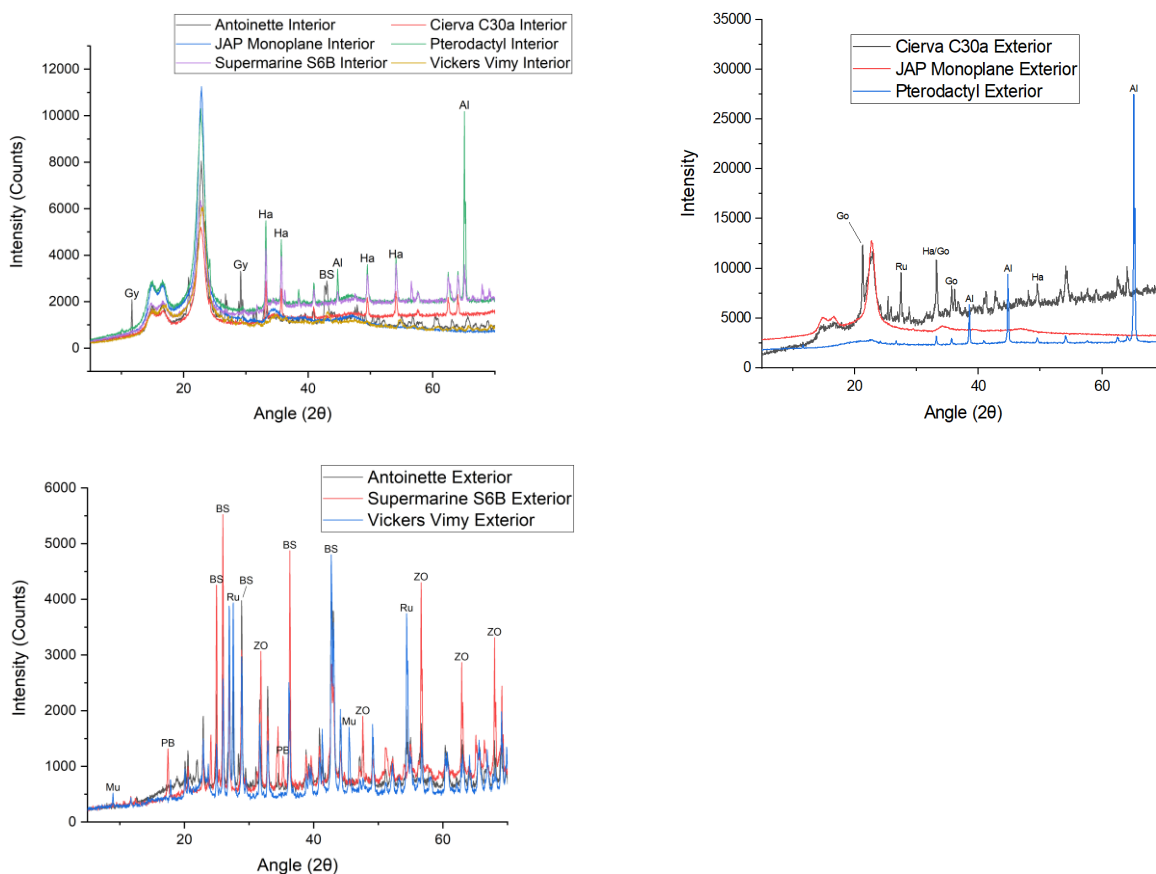


Figure 7-17: XRD patterns of samples taken from aircraft on display in *Flight* at the Science Museum. Gy = gypsum, Ha = haematite, Go = Goethite, Al = aluminium, BS = barium sulphate, Mu = muscovite, Ru = rutile, ZO = Zinc Oxide, PB = Prussian Blue

Also relatively simple are the XRD patterns of the red surfaces of the Cierva C30a and Pterodactyl, which both comprise haematite. Aluminium was also detected on the red, internal surface of the Pterodactyl, though the signal was even stronger when the reverse, silver side was analysed and haematite was no longer detected.

The exterior paint surfaces of the aircraft were found to contain broadly similar compounds. The pattern of the exterior of the Antoinette Monoplane was dominated by barite, though zinc oxide was also detectable, the two components often being found together in a paint filler called lithopone. Also detected on the Antoinette paint surface were rutile and gypsum. Analysis of the paint layer of the Vickers Vimy identified muscovite, barite and

rutile and in the external paint layer of the Cierva C30a haematite, rutile and goethite were identified. On the interior surface of the Supermarine, Prussian Blue and haematite were identified, as was also found on the exterior surface, though in addition barite, zinc oxide and gypsum were also identified.

7.4.5. Raman Spectroscopy Results

The problem of fluorescence meant that the collection of spectra proved impossible or of very limited value in many instances. Spectra obtained of the Cody Bi-Plane paint, JAP Monoplane and Roe Tri-plane from the technical files each had a peak at 985cm^{-1} indicative of barium sulphate (Harroun *et al.*, 2011). A peak at 1051cm^{-1} on the JAP monoplane spectrum may also be indicative of lead carbonate, though this was not detected in the Roe Tri-plane spectrum as would be expected from the XRD results. In the Cody Bi-Plane spectrum there were also large peaks at 608 and 444 characteristic of titanium dioxide.

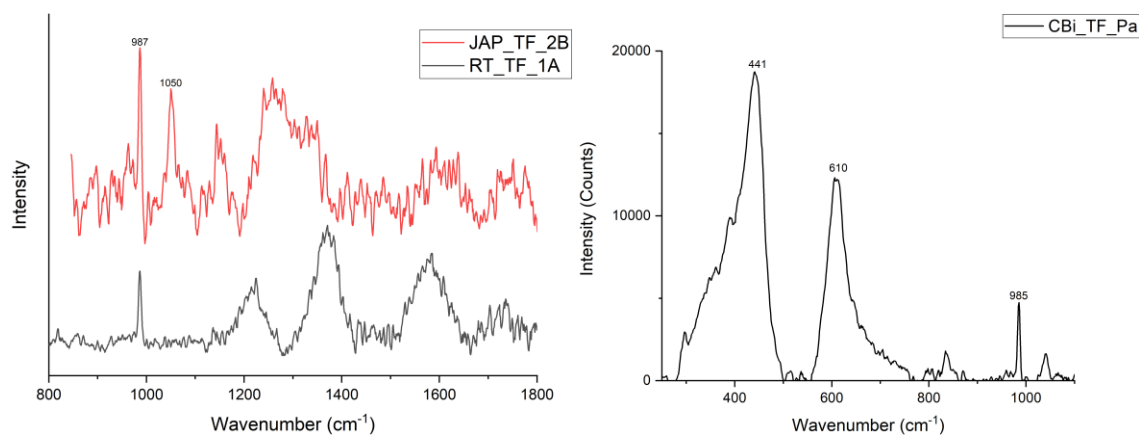


Figure 7-18 Raman spectra of samples taken from the technical files of doped-fabric aircraft at the Science Museum

From the gallery samples spectra obtained from the interior of the Cierva C30 and Pterodactyl are nearly identical and are attributed to iron oxide whilst the Vickers Vimy spectrum is similar to that of the Cody Bi-Plane, and is indicative of titanium dioxide.

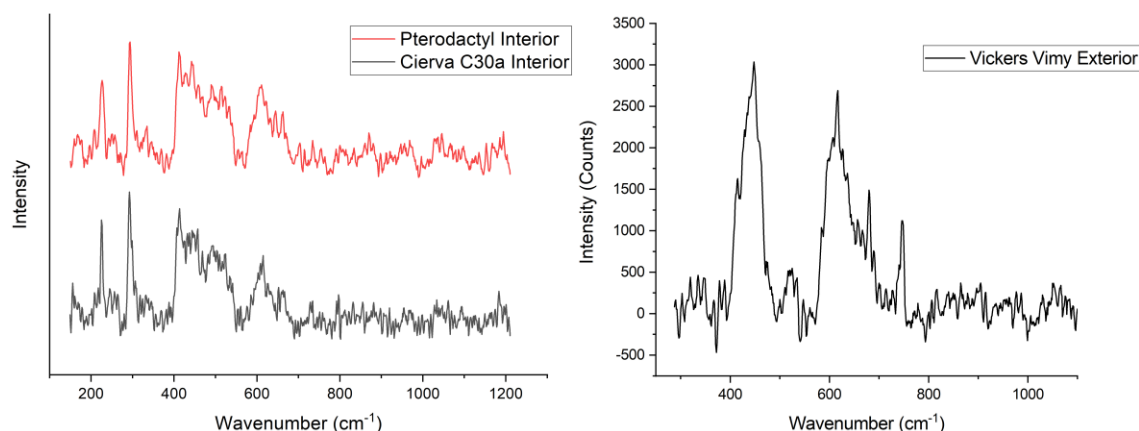


Figure 7-19 Raman spectra of samples taken from aircraft on display in Flight at the Science Museum

7.5. Discussion

The combination of analytical techniques applied here has proved effective at characterising the material composition of the doped-fabric aircraft samples available, and the results of the different techniques have generally been consistent. In the case of the JAP Monoplane technical file, for example, the evidence that the dark surface coating is a lead white based paint is supported by both the use of XRF, which identified the presence of lead in the sample, and Raman spectroscopy, which detected lead carbonate.

The use of multiple techniques, moreover, has helped ensure components which might otherwise have been missed have been identified. Had only XRD been performed on the JAP technical file material, for instance, the presence of lead carbonate would not have been detected, the reason for which is not certain though it may be that it is in too low a concentration for detection by XRD. Having said this, there is no guarantee that the identifications made in the above results section are complete and that every compound present was identified. Manganese, for example, was detected in the JAP Monoplane tech file material, but none of the other techniques used helped confirm what compound or role this manganese might play, or if it might be contamination from another source.

It is also worth considering the potential complexity when material compounds overlap between paints and dopes, and potential problems of deconvoluting their signals. In the case of the Cierva C30a, for example, FTIR-ATR produced a strong signal for cellulose nitrate when the green paint layer was analysed in isolation from the fabric, but much weaker ones on the fabric interior and fabric surface with the paint layer removed. This could be attributable to the paint layer peeling off the dope film with it when removed from the fabric surface, as appears to have happened with the Vickers Vimy gallery sample and Cody Bi-Plane technical file material.

Alternatively, however, cellulose nitrate is also used as a binder meaning that it could be an intrinsic ingredient of the paint, and that the cellulose nitrate signal is a component of the paint only and is not connected with a dope on the fabric.

This seems unlikely, however, as the red layer contains iron oxide and seems consistent with a dope of a type comparable to that of the Red Neogene having been applied, and as was also found on samples taken from the Pterodactyl and Supermarine S6B. The cross section of the Cierva C30a fabric, moreover, shows the fibres bonded together as expected from a doped material. It could be, therefore, that the cellulose nitrate is a component of both the dope on the fabric and the binder in the paint. This demonstrates, however, how results regarding one part of the doped-fabric structure may influence and distort the interpretation of other parts of the structure which may not be easily isolated.

The materials and doped-fabric structures characterised in this study are generally consistent with those described in chapter 2, where the historic literature established that doped-fabrics generally consist of a closely woven fabric substrate impregnated with a cellulose ester dope. The only material which appears to have a significantly different construction from this was that found in the Roe-Triplane technical file, which is comprised of a loose netting material which supports a thin covering coated with a lead white based paint.

This construction, although unique among the aircraft studied here, is attested to within the technical file evidence for this aircraft from correspondence with A.V. Roe, the fabricator, in which he discusses how the aircraft was covered with a fabric backed packing paper instead of fabric. This suggests that the technical file material, although unusual, is probably a better representation of what would have originally covered the Roe-Triplane than a conventional doped-fabric. It also illustrates the need for caution if making assumptions about the composition and structure of doped-fabric aircraft (if indeed the Roe Triplane should be termed such), especially very early aircraft which may have less conventional designs. This also demonstrates the importance of combining archival research with analytical study when approaching historic objects, as it is through the use of both approaches that a fuller understanding of the material is reached.

What would be of great interest would more information as to how the materials currently on the Roe Tri-plane as displayed in *Flight* compare to those in the technical file, and if they are based on the same construction or if the *Flight* aircraft is now covered in a doped-fabric skin similar to the other aircraft studied. As no suitable areas of damage or other openings for sampling were found on the Roe Triplane, this question remains open for future investigation.

The analysis of the more conventional types of doped-fabric found in the technical files and taken from *Flight* indicate that variation has occurred between the structures of the doped-fabrics in terms of the number and types of layers used to construct the coverings. The simplest doped-fabrics, such as the Vickers Vimy and Antoinette technical file material, seem to have been treated with only one type of unpigmented dope without any further pigments or layers being added but more complex dope constructions involved the combination of different dopes in layered structures.

These could include a red base layer where the red pigment in all cases has been identified as haematite, and a silver coloured upper layer containing aluminium powder. Where used together, these two dope types were typically applied as expected from the literature, with the iron oxide applied first and the aluminium oxide layer above this to act as UV protection. Only in the case of the Se5a technical file material does it appear that something different may have been done as in this instance the red colour has not penetrated throughout the fabric suggesting a clear base coat may underlie it.

Several of the aircraft were also finished with a paint layer above the dopes. These paint layers generally contain typical components and additives which would commonly be found in a paint, including barium sulphate, zinc oxide, calcium sulphate, rutile (a polymorph of titanium dioxide) and mica. These are typical paint fillers used to improve opacity and the covering power of paints. Barium sulphate and zinc oxide, for example, are often used in conjunction to create a compound called lithopone which is used to whiten paints.

Rutile was detected on the gallery samples from the Vickers Vimy, Antoinette Monoplane and Cierva C30a, which indicates that these paints are post 1930, as it was only from the late 1930's onwards that rutile could be mass produced and was used extensively in paints, replacing anatase, a rarer and more expensive form of titanium dioxide (Conservation and Art Materials Encyclopedia, 2018)(Clark, 2007). The presence of rutile in the gallery sample paints, however, is unsurprising given the archival evidence indicating these aircraft were recovered as recently as the 1960's and 1970's since when titanium dioxide paints have been common.

In the case of Cody Bi-Plane technical file material, detecting rutile in the paint does not help confirm a possible date range when the fabric covering was applied since, although the paint is likely to date from after the 1930's, it could be that the doped-fabric substrate is older and pre-dates the paint which was applied separately at a later date. Unfortunately, there is no evidence to confirm whether the paint was applied with the fabric or during a later, separate treatment, and this highlights the difficulties in interpreting historic objects where multiple layers of separate activity may become convoluted and indistinguishable, and the caution therefore required in interpreting such objects.

Two samples from the technical files, those of the JAP monoplane and Roe Triplane were also found to contain lead carbonate, also known as lead white, a common pigment especially prior to the 1930's after which rutile was increasingly used on health and safety grounds (Davis, 1982). The fact that both surfaces of the Roe Triplane and JAP Monoplane are darkened is not inconsistent with lead white, which studies have suggested is prone to reaction with hydrogen sulphide in the air causing it to darken (Barker *et al.*, 2006). The presence of lead carbonate therefore indicates that the technical file material for these two aircraft could pre-date the 1930's, though again such statements should be made with caution as the material could still post-date the 1930's. The identification of lead white also demonstrates that these surfaces would potentially have been a very different, much lighter colour when first applied, and that chemical changes have led to alterations in the material appearance over time.

Pigments were also identified in other paint surfaces. The dark blue layer of the Supermarine S6B is likely attributable to Prussian Blue, the first synthetic pigment to be produced by the oxidation of ferrous ferrocyanide salts and so likely available during the original manufacture as well as any later interventions (Kirby and Saunders, 2004). The presence of Prussian Blue may be of concern to conservators since it has been found to fade under certain conditions, particularly light exposure, and so extra care as to display conditions for this object may be needed in terms of light exposure. The earthy brown and cream yellow of the Cierva C30a could in part be attributable to the addition of goethite, a common earth pigment more commonly known as Brown Ochre, with colours ranging from yellow to brown.

When comparing the results from the technical file and gallery samples, one notable shift appears to be a change from cellulose acetate based dopes which are favoured in the technical file materials to cellulose nitrate on the later, re-covered gallery samples. In the case of the gallery samples, cellulose nitrate was detected on 5 of the 6 samples, whilst only 1, the Vickers Vimy, had a cellulose acetate coating. The technical file materials, in contrast, held 3 samples with a cellulose acetate dope, while only 1 appeared to have been doped with cellulose nitrate.

This suggests that there may have been a shift away from cellulose acetate dopes to cellulose nitrate but it is not clear whether such a shift was a conscious decision undertaken during the restorations, such as to take advantage of perceived benefits of cellulose nitrate over other dope types or a desire for what might have been considered more authentic, or a decision driven by pragmatism and the availability of materials. Whether there is necessarily even a shift from cellulose acetate based dopes to cellulose nitrate ones moreover remains open to debate due to problems in making direct comparisons between the gallery and technical file materials, as not all those aircraft sampled from the technical file are represented by samples taken from gallery and vice-versa.

In only three cases, that of the Vickers Vimy, JAP Monoplane and Antoinette Monoplane, was material obtained from both gallery and the technical file.

A comparison of the JAP Harding Monoplane fabrics from gallery and the technical file are interesting since they indicate significant differences between the two sources. The type of fabric from the technical file to gallery sample is altered from a plain weave to a 4/1 twill weave, and the type of dope alters from cellulose acetate to cellulose nitrate. In addition, no surface finish has been applied to the JAP Harding on display in *Flight*, unlike the technical file material with its dark brown coating. This indicates that the aircraft may have had a very different appearance before it was re-covered to how the aircraft is presently displayed.

The reason for these differences are not documented and the motive for it is not immediately obvious. It may be that the fabric retained in the technical file is not representative of the entire aircraft, and that the material used in the recovering is a more faithful reproduction of another fabric type not retained. It may also be that the recovering was simply undertaken with the most convenient materials to hand without concern for duplicating the original.

A similar issue arises when comparing the samples taken from the Vickers Vimy in *Flight* and the material retained in the technical file. Although the type of dope used and fabric weave are broadly consistent, the most obvious change is that a layer of yellow paint has been applied to the Vickers on display. Again, although it is mentioned in the technical file that the museum planned to undertake this work in the 1970's (chapter 3.1), the reasons and motivation for it are not documented and so cannot be meaningfully judged.

This type of discrepancy is also found in the material of the Antoinette Monoplane in which the technical file material is unpainted, whilst the gallery sample is. Such a difference, however, may be due to the origin of the fabric. It is known that the gallery sample was taken from the painted fuselage section, but the precise origin of the technical file materials is not known. It may be then that the Antoinette technical file material originates from an unpainted area of the aircraft such as are still visible in the aircraft current form in the empennage and wings, but a lack of context about the material prevents more in-depth investigation of these concerns.

This raises one of the most significant problems when interpreting these results, in that very little is known about the material kept in the technical files. One might question, for example, why these particular pieces of fabric were kept in place of others; was it because they are standard pieces of fabric representative of the aircraft as a whole or was there something that marked them out as special and of greater interest, or perhaps no particular thought was given to the issue and the first piece picked off the floor was selected.

The above demonstrates the problems in assessing materials for originality and authenticity, and how analytical results as to material composition are insufficient on their own without historical context to make such judgements. The doped-fabrics, for example, are generally made from materials and compounds which might be expected of a traditional doped-fabric aircraft suggesting that they are reasonably authentic, but this overlooks some anomalies, such as the addition or loss of coatings, as well as changes in dope type and fabric weave.

It seems, therefore, that the presentation and interpretation of these aircraft may have been altered in significant ways which may be a representation of the curatorial voice during the restoration project, but cannot readily be accounted for based on a technical comparison of the gallery and technical file materials. This would potentially make justification of a further re-covering from a conservation perspective view point straightforward, to return the object to an appearance more in keeping with fabric found in the technical file, but such decisions should still be made with care as the authenticity and originality of such material is itself questionable.

While differences between the technical file and gallery materials of some aircraft have been demonstrated, this has not been possible for the majority and may represent a few isolated cases. Identifying that a doped skin is in some respects different to that of another covering from the same aircraft but from a different period, moreover, does not necessarily answer the question as to which is more accurate, and whether the technical file material is accurate or itself the result of numerous re-interpretations and alterations over years to alter the aircraft appearance.

Finally it should be borne in mind that chemical changes in the materials may have resulted in differences between certain results. Peaks around 3500 and 3400cm⁻¹ in the FTIR-ATR results, for example, are attributed by Feller to the formation of hydroperoxide groups which form due to photo-oxidation and other degradation reactions (Feller, 1994). This may explain why such peaks are more prominent in historic samples compared to the modern materials where they are not detected. Other changes in FTIR spectra which may occur on ageing include shifts in the position, intensity and ratios of peaks, such as the carbonyl peak. This study has limited itself to a qualitative identification of the materials used in manufacturing of aircraft, and further study of doped-fabric deterioration mechanisms under controlled conditions would be needed to better understand the processes taking place in the historic materials (Wilhelm and Cardette, 1994; Ali *et al.*, 2001; Garside and Wyeth, 2003; Quye *et al.*, 2011).

7.6. Summary

Where it has been possible to obtain samples from the aircraft on display in *Flight* or from the materials retained in the technical file it has been possible to establish many of the main compounds and materials used in their manufacture. The materials indicate that most aircraft, both in their current form and in previous ones, were constructed from materials appropriate to a historic, doped fabric aircraft.

Where comparison of technical file and gallery materials for the same aircraft were possible, some striking differences have emerged. Potential alterations included the type of fabric used, the type of dope applied and change in the painted finish. This suggests that the form and appearance of the aircraft has altered due to interventions undertaken by museum staff, but a lack of context as to how and why these decisions were made, and how representative the technical file material is as to the aircraft's prior appearance, limits judgement or evaluation as to the appropriateness of such interventions.

Such interventions, moreover, highlight the dangers of assuming objects within museums are historically accurate, static representations of the past, and the importance of a critical awareness as to how such objects may have been manipulated and altered over time. The discussion of dating issues, for example, emphasised that whilst certain compounds may enable an approximate date range for certain parts of a doped-fabric structure, such as a paint layer, extrapolating this date to the surrounding material may be unwarranted. A combination of both analytical and archival information is required, therefore, when evaluating such objects, if they are to be interpreted as fully and meaningfully as possible.

8. The Effect of Doping Irish Linen Aircraft Fabric

8.1. Introduction

The purpose and requirements of doped-fabrics as functioning parts of an aircraft have been discussed in chapter 2.2, but the properties of doping within a conservation context, i.e. when doped-fabric patches are applied, is poorly understood. A better understanding of the drying mechanism of a doped-fabric and how it affects a fabric's properties is therefore needed regarding:

- The drying rate of the dope
- Differences in behaviour between the warp and weft directions respectively
- The impact of doping compared to other conservation adhesives that could be substituted on patches

The drying rate is an important issue since, as discussed in 4.5.3, a proposed cause of doped-fabric failure is that dope films may continue drying, and consequently contracting, for many years after application leading to eventual failure of the skin or distortion of the frame. This suggestion, although not supported by any analytical work to date, has been shown to have entered wider conservation discussions and therefore needs addressing as to whether this could feasibly contribute to long-term failure of doped-fabric skins, and would also be an issue in the use of doped-fabric patches if they were to continue contracting over many years.

Consideration of how warp and weft directions may differ during doping is also necessary to better understand whether patch orientation may be affecting the performance of the treatment methodology. The motivation for this project was a concern that shrinkage of doped-fabric patches was causing further damage to the doped-fabric skins of objects and attempting to quantify the potential strain and loads in the two directions when dope is applied to fabric is necessary to begin assessing whether such concerns are justified.

The final outcome listed is a comparison of the drying mechanism of common conservation adhesives to dope when applied to fabric. This matters since alternatives to using dope may be desirable when developing conservation methodologies. Greater information about the behaviour of these other options compared to dope, can be used to better inform treatments and decision-making processes.

8.2. Experimental

8.2.1. SEM Microscopy

Cross sections of 9F1 Irish Linen both untreated and after doping with 9701 Randolph Tautening Butyrate Dope were imaged with a JSM-5610LV SEM using secondary electron imaging mode (SEI). Cross-sections were cut

from doped-fabric panels prepared according to the process described in chapter 6.1 using a scalpel, then mounted on an aluminium stub and gold coated. A maximum excitation voltage of 15kV was used to avoid sample damage.

8.2.2. The Strain of 9F1 Irish Linen Panels during Doping

Panels of 9F1 Irish Linen aircraft fabric were prepared as described in chapter 6.1, and for reference Table 6-1 which describes the doping process is repeated below. The results of the strain measured during Step 2 of the doped-fabric panel preparation process, when dope was applied to the fabric, will be presented here. The measurements of each strain gauge has been zeroed to the moment at which the first coat of dope was applied to allow for comparison between gauges.

Coat Number	Dope Volume (ml)	Acetone (ml)	Direction	Drying Time (hours)	Application Method
1	15	15	Weft	1	Brush
2	15	15	Warp	1	Brush
3	30	0	Weft	1	Brush
4	30	0	Warp	1	Brush
5	30	0	Weft	1	Brush
6	30	0	Warp	1	Brush

Table 6-8-1: Dope application process

For panels prepared with gauges in configuration 2, only gauges in the central position for warp and weft have been reported. This is to avoid potential edge effects when approaching the edge of the acrylic frame which may restrict the fabric response to the dope.

8.2.3. The Effect on Load of Doping 9F1 Irish Linen at Constant Extension

Pieces of 9F1 Irish Linen measuring 15x70mm in both the warp and weft directions respectively were prepared for mounting in a Gatan M2000E 2kN tensile frame, the jaws of which were lined with archival card to prevent their surfaces damaging the fabric.

The samples had an initial starting extension of 10mm and, once mounted, were extended at a constant rate of 0.4mm/min until a load of 20N was reached, the load and extension of the jaws were recorded every 2 seconds. Once a load of 20N was reached, the samples were held at constant extension, and left undisturbed for a minimum of 12 hours as the load stabilised.

Once the load was stable, samples were coated with a conservation adhesive or Randolph 9701 Clear Tautening Butyrate dope. The conservation adhesives tested were:

- 50% Paraloid B72 (ethyl methacrylate) (w/v) in 50:50 IMS and acetone
- Lascaux 498H (butyl acrylate)
- 5% Klucel G (hydroxypropylcellulose) (w/v) in de-ionised water

Two samples were treated in the weft direction for each conservation adhesive. For the Randolph 9701 doped samples, two samples were tested in the weft direction, and one in the warp direction to compare the behaviour in both directions as for the strain gauges. Table 8-2 lists the samples prepared.

For each sample a total of 6 coats of the adhesive or dope were brushed on at 1 hour intervals, each coat consisted of 0.1g of the solution. For Randolph 9701 Butyrate dope, the first two coats were diluted 50% v/v in acetone and coats 3-6 were undiluted. This was done to replicate doping practice at the Science Museum and the procedure used for doping the fabric panels being monitored using strain gauges.

Sample Name	Fabric Substrate	Fabric Direction	Compound Applied
We_RBD_1	9F1 Irish Linen	Weft	Randolph 9701 Butyrate Dope
We_RBD_2	9F1 Irish Linen	Weft	Randolph 9701 Butyrate Dope
Wa_RBD_1	9F1 Irish Linen	Warp	Randolph 9701 Butyrate Dope
We_PB72_1	9F1 Irish Linen	Weft	50% Paraloid B72 (w/v) in 50:50 IMS and acetone
We_PB72_2	9F1 Irish Linen	Weft	50% Paraloid B72 (w/v) in 50:50 IMS and acetone
We_Las_1	9F1 Irish Linen	Weft	Lascaux 498H
We_Las_2	9F1 Irish Linen	Weft	Lascaux 498H
We_KIG_1	9F1 Irish Linen	Weft	5% Klucel G (w/v) in de-ionised water
We_KIG_2	9F1 Irish Linen	Weft	5% Klucel G (w/v) in de-ionised water

Table 8-2: Samples used for tensile testing the effect on load of applying dope or conservation adhesive to 9F1 aircraft linen

8.2.4. Tensile Testing Doped-Fabric to Failure

Three different types of material were prepared for this experiment:

- Undoped 9F1 Irish Linen
- 9F1 Irish Linen doped with Randolph 9701 Butyrate dope
- Technical file material

Samples of undoped 9F1 Irish Linen measuring 70x15mm in both warp and weft were cut from the roll of fabric purchased for making doped fabric panels, whilst the doped-fabric samples measured 30x15mm and were cut from panels of doped-fabric made using the standard doping process already described. A list of samples is provided in Table 8-3.

Material Type	Direction	Dimensions (mm)	Source	Number of samples
Undoped 9F1 Irish Linen	Warp	70x15	Fabric Roll	7
Undoped 9F1 Irish Linen	Weft	70x15	Fabric Roll	12
9F1 Irish Linen doped with Randolph 9701 Butyrate dope	Warp	30x15	Doped fabric panel	6
9F1 Irish Linen doped with Randolph 9701 Butyrate dope	Weft	30x15	Doped fabric panel	6
Technical File	X	30x15	Antoinette Cody Bi-Plane JAP Monoplane Se5a aircraft Vickers Vimy	10
Technical File	Y	30x15	Antoinette Cody Bi-Plane JAP Monoplane Se5a aircraft Vickers Vimy	10

Table 8-3: Samples tested to failure at a constant rate of extension

The historic samples measured 30x15mm and were cut from the technical file material discussed in chapter 6.3.1. Four samples (two in each weave direction) were taken from five aircraft files, making 20 historic samples in total. The shorter length of the doped and historic samples compared to undoped fabric samples was because the rigidity of these samples limited the length that could fit between the jaws of the frame and also reduced the amount of historic material sampled.

A 1mm cut was made in the sides of every sample at the centre of its length and samples were then conditioned to the same RH conditions by sealing them in a chamber with a saturated salt solution of magnesium nitrate

hexahydrate which created a stable RH environment of 50%. Samples were conditioned in this climate for 1 month.

The samples were mounted in the Gatan M2000E 2kN tensile frame at a starting extension of 10mm, with the side incisions centred between the jaws, after which the jaws were extended at a constant rate of 0.4mm/min until failure occurred, the load and extension recorded every 2 seconds. The experiment was conducted in ambient lab conditions.

8.3. Results

8.3.1. SEM Microscopy

Even before the use of SEM microscopy a few observations about the drying of the doped panels may be made. On removing panels of doped-fabric from the frames it was found that all panels curled up in the weft direction, with the doped side (exterior) under compression and the fabric side (interior) extension. No panels curled up in the warp direction on being released from the frames (Figure 8-1).



Figure 8-1: Doped-fabric panels of 9F1 Irish Linen treated with 9701 Randolph Butyrate dope after removal from the acrylic frame

The influence of the dope is clearly observable in SEM micrographs taken of 9F1 Irish Linen cross sections in a doped and non-doped state (Figure 8-2). In the non-doped state, the fibres are free to unravel once cut, but in the doped state are bound together in the doped film matrix. Also observable is an apparent difference in the contraction of yarns, with portions of the yarn on the doped side undergoing a greater contraction, though more samples require measuring to confirm this. Finally, it is worth noting in these images the difference in crimp factor, whereby the weft thread can be seen to be relatively straight deviating approximately 23°, whilst the

warp yarn must deviate approximately twice this to pass around the weft threads. More detailed analysis would be needed to provide a more reliable figure for crimp, but this measure enables an appreciation as to the difference that exists between the two fibre directions.

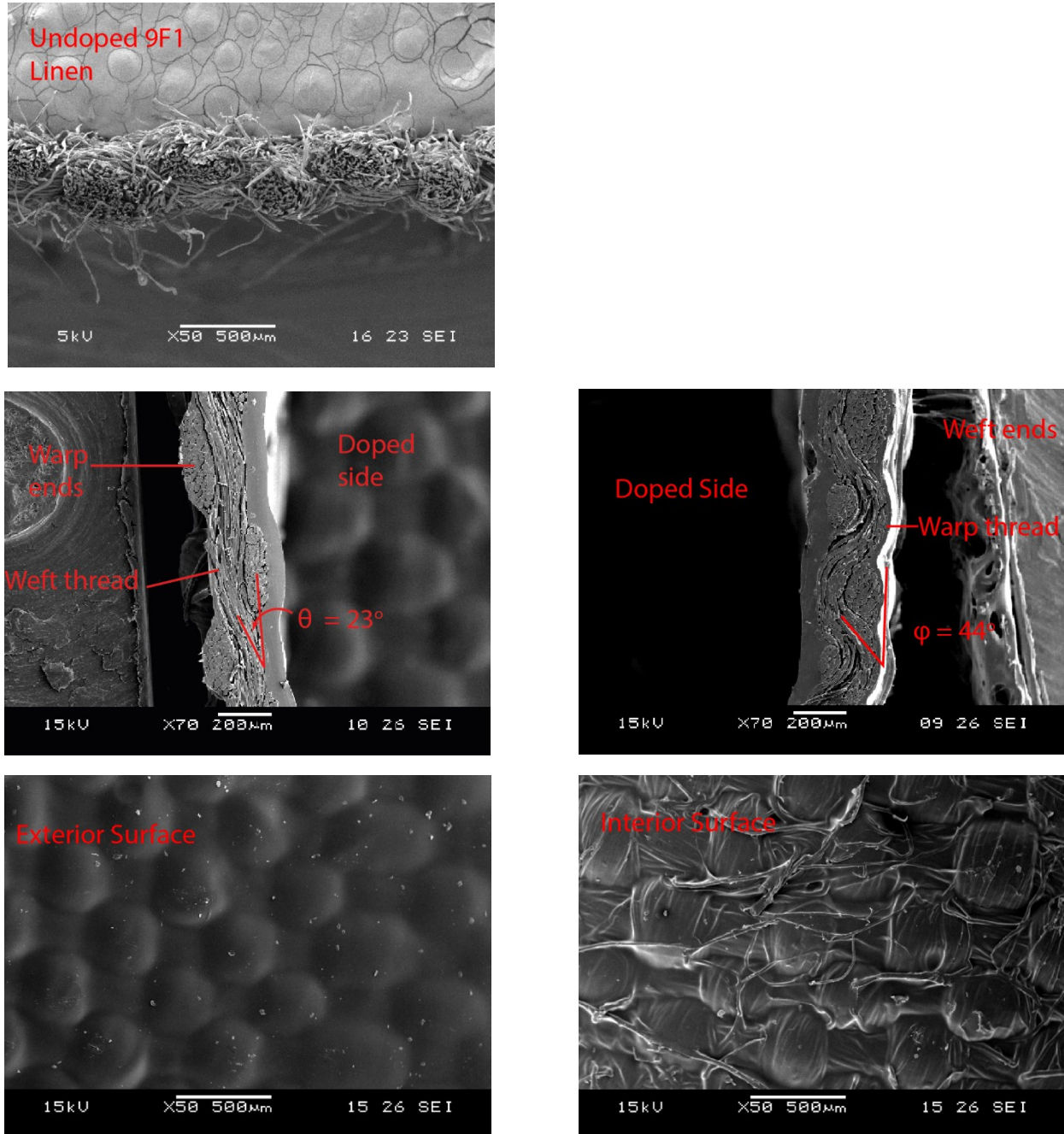


Figure 8-2: SEM micrographs of 9F1 Irish linen undoped and doped with 9701 Randolph Butyrate dope. From top left to bottom right cross section of un-doped 9F1 Irish Linen, cross-section of doped warp yarn ends, cross section of doped weft yarn ends, the exterior surface of the doped-fabric, the interior surface of the doped-fabric

A comparison of the interior and exterior surface of the doped samples highlights the smoothing properties of the dope. On the interior surface considerable surface irregularity can be seen due to the presence of loose fibres. Such irregularities are not seen on the exterior, however, where the surface is smooth and consistent, the dope seemingly having filled in all the interstices between yarns, though with some topographical features where the dope has settled into deeper hollows than in other areas.

8.3.2. The Strain of 9F1 Irish Linen Fabric Panels during Doping

The strain of the fabric panels shown in the warp and weft direction during the six hours from when the first coat of butyrate dope was applied are shown in Figure 8-3, and the average strain across all six panels is shown in Figure 8-4. Although coats were meant to be brushed on 1 hour apart, there was some drift in timings which accumulated over the course of the experiment so that coat 6 appears to have been applied considerably before 300 minutes when it should have been, but was only slightly out relative to coat 5 which preceded it.

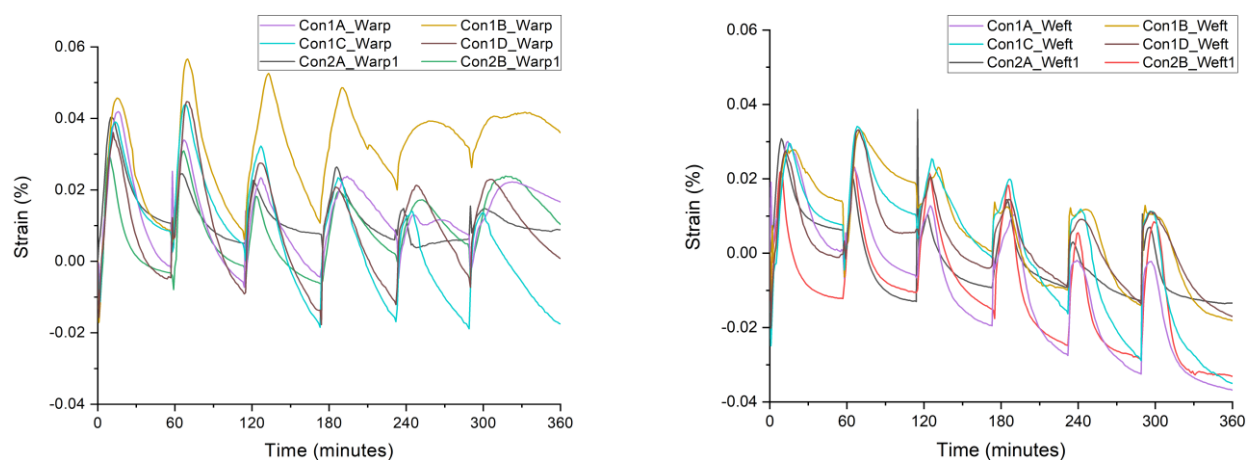


Figure 8-3: Strain measured in the doped-fabric panels in the warp (left) and weft (right) direction during application of Randolph 9701 Clear Butyrate Dope

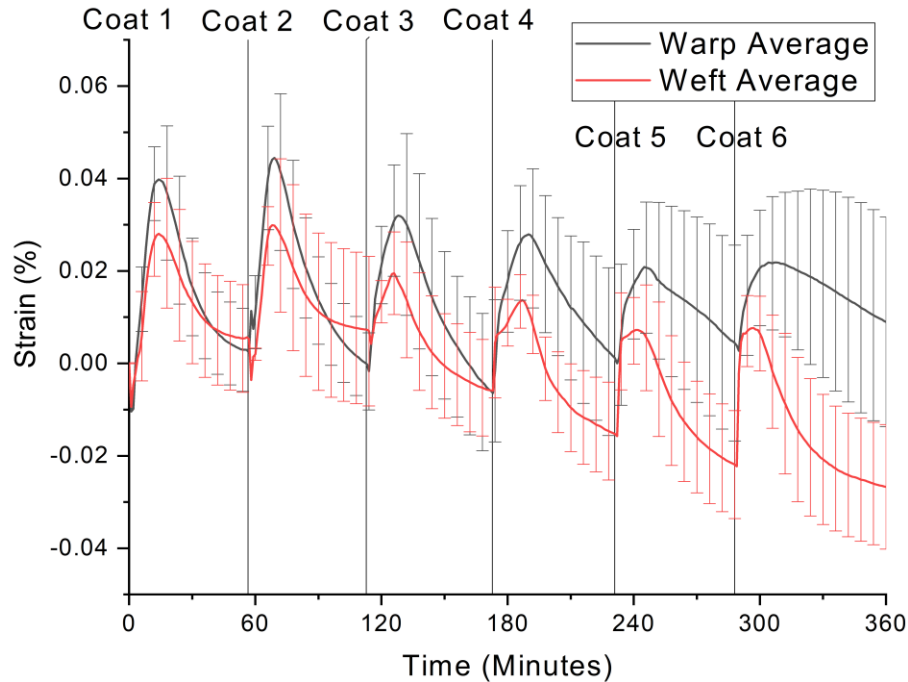


Figure 8-4: The average strain response of type 9F1 Irish Linen fabric panels against time when Randolph 9701 clear tautening butyrate dope is brushed on (Error bars represent a 95% confidence interval assuming a t-distribution at 10 minute intervals)

On application of dope coats 1 and 2 the first response of the fabric was a rapid contraction, but this initial contraction became much reduced or with increasing numbers of coats. After any initial contraction the panels there followed an increase in strain which eventually reached a maximum, followed by contraction which in some cases began to tail off or was cut short by application of the next coat of dope.

The maximum strain with each coat is shown in Figure 8-5, and it can be observed that with successive coats of dope the maximum strain in warp and weft decreased. The average strain measured at the end of each coat, prior to application of the next, is also shown in Figure 8-5. While coats 1 and 2 do not appear to cause a significant overall change in strain, from coat 3 onward the two directions begin to separate as the strain in the weft decreases with each coat applied but the warp strain increases from coat 3.

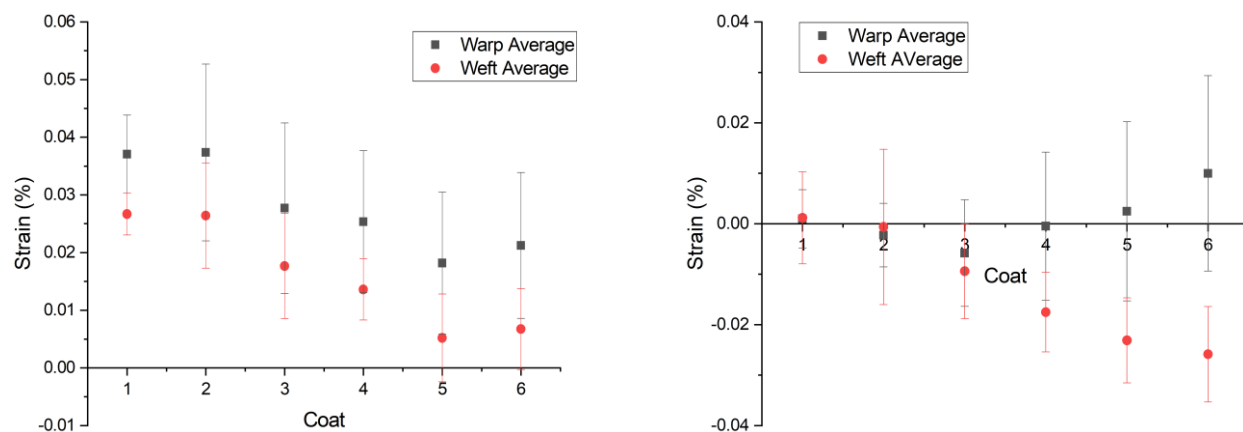


Figure 8-5: Left, the maximum average strain measured during each coat application. Right, the average strain measured prior to application of the next coat. (Error bars represent a 95% confidence interval assuming a t-distribution)

The response rate of warp and weft to doping was also observed to differ when time to reach maximum strain, and hence start the final contraction, was examined (Figure 8-6). The time in which weft responds has a downward trend with increasing coats whilst the warps increases, though the variability between panels in the warp direction also increases markedly with increasing number of coats. This indicates that compression starts in the weft earlier than the warp and may be a factor in the greater compression measured at the end of each coat.

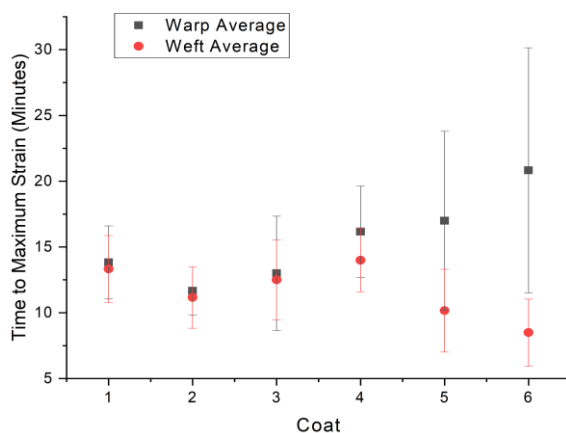


Figure 8-6: Average time to reach maximum strain in warp and weft with each coat of dope (Error bars represent a 95% confidence interval assuming a t-distribution)

A summary of values for the maximum strain, strain at the end of each coat application and the time to reach the maximum strain are provided in Table 8-4 and Table 8-5 for warp and weft respectively.

Coat	Maximum Strain (%)	Strain at end of coat (%)	Time to Maximum Strain (minutes)
1	0.0371 ±0.0068	0.001 ±0.0058	13 ±3
2	0.0374 ±0.0153	-0.0023 ±0.0063	12 ±2
3	0.0277 ±0.0148	-0.0058 ±0.0105	13 ±4
4	0.0254 ±0.0123	-0.0005 ±0.0147	16 ±3
5	0.0182 ±0.0123	0.0025 ±0.0178	17 ±7
6	0.0212 ±0.0127	0.001 ±0.0194	21 ±9

Table 8-4: Warp average values per coat for maximum strain, strain at the end of each coat cycle and the time to reach maximum strain (Error values represent a 95% confidence interval assuming a t-distribution)

Coat	Maximum Strain (%)	Strain at end of coat (%)	Time to Maximum Strain (minutes)
1	0.0267 ±0.0036	0.0012 ±0.0091	13 ±3
2	0.0264 ±0.0091	-0.0006 ±0.0154	11 ±2
3	0.0177 ±0.0091	-0.0094 ±0.0094	13 ±3
4	0.0136 ±0.0053	-0.0175 ±0.0079	14 ±2
5	0.0052 ±0.0076	-0.0231 ±0.0084	10 ±3
6	0.0067 ±0.0070	-0.0259 ±0.0095	9 ±3

Table 8-5: Weft average values per coat for maximum strain, strain at the end of each coat cycle and the time to reach maximum strain (Error values represent a 95% confidence interval assuming a t-distribution)

The response of the doped panels during the 48 hours after application of the first coat of dope also reveals differences between warp and weft (Figure 8-7). The contraction in the weft direction continued throughout the 48 hours, though the rate did stabilise at around 2400 minutes. The average strain measured in the warp, in contrast, began to increase at around 800 minutes. This indicates that approximately 5 or 6 hours after application of the 6th coat of dope the force of compression, though still apparently acting in the weft direction, is no longer dominant in the warp.

The minimum average strain measured in the warp before it began to increase at 783 minutes and was $-0.01327\% \pm 0.01654$. At the same time the average strain in the weft was $-0.03397\% \pm 0.01292$, a compression over 2.5 times that in the warp.

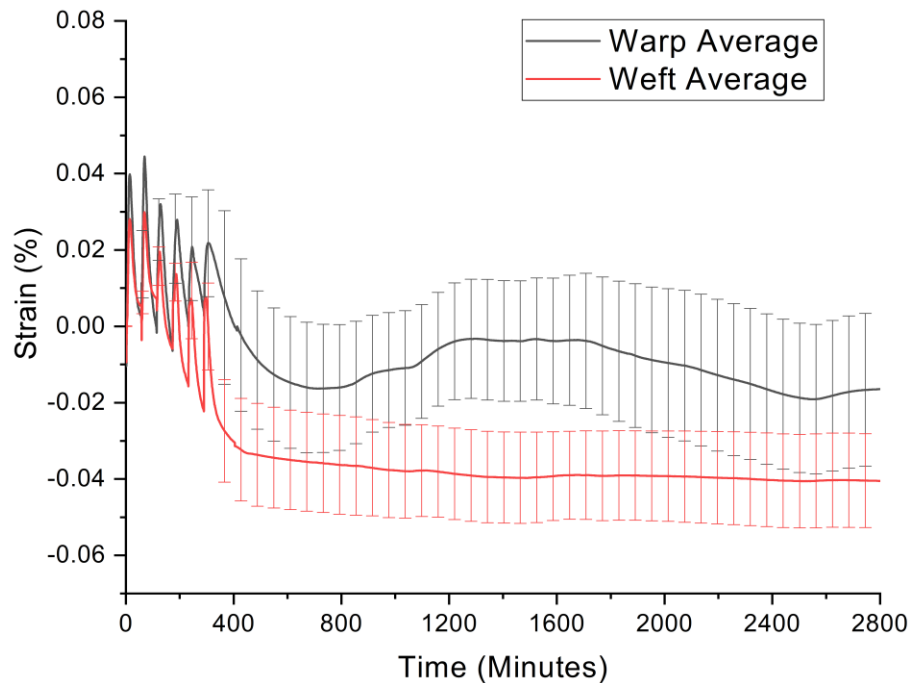


Figure 8-7: Average strain of doped-fabric panels drying in ambient conditions in the 48 hours after coat 1 of dope applied. (Error bars represent a 95% confidence interval assuming a t-distribution at 1 hour intervals)

8.3.3. The Effect on Load of Doping 9F1 Irish Linen at Constant Extension

The load exerted in the warp and weft over time as successive coats of Randolph 9701 Clear Butyrate Tautening dope were brushed onto pieces of 9F1 Irish Linen is shown in Figure 8-8. In coats 1 and 2 there was an immediate, rapid increase in load once the dope was applied before it decreased to below the starting load. During coat 1 the load then became reasonably stable though an increase in load did occur in coat 2 on sample We_RBD_1.

A change in behaviour occurs from coat 3 onwards. When coat 3 was applied to the weft samples there was an initial drop in load, before a small increase and decrease again. The size of the initial drop in load became more pronounced with each coat, and the following 'bump' less and less pronounced. This initial reaction was followed by a large increase in the load which was cut short by application of the next coat. For the warp sample, Wa_RBD_1, at coat 3 no decrease in load was noted, only an increase. From coat 4, however, it

responded in a similar manner to the weft samples, with an initial rapid drop in load followed by an increase which then gradually levelled off.

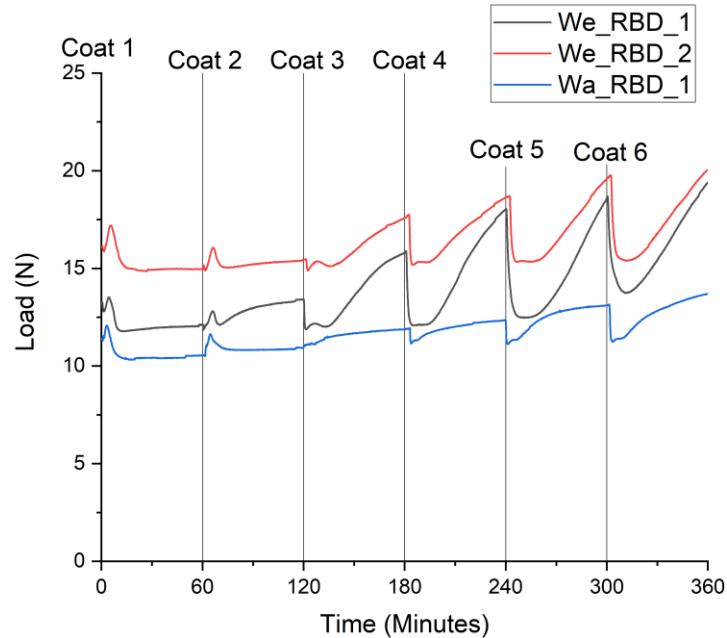


Figure 8-8: Load on a piece of 9F1 Irish Linen held at constant extension with successive coats of Randolph 9701 Butyrate dope applied

Each initial decrease in load from coat 3 onwards appears to return to a reasonably consistent base level and, with successive coats of dope, the final load exerted on the sample tends to increase (Figure 8-9). The increase in load between coats is generally greater in the weft samples compared to the warp sample, and the greatest change in load between coats occurred with the application of coat 3, after which the effect of doping between coats reduced.

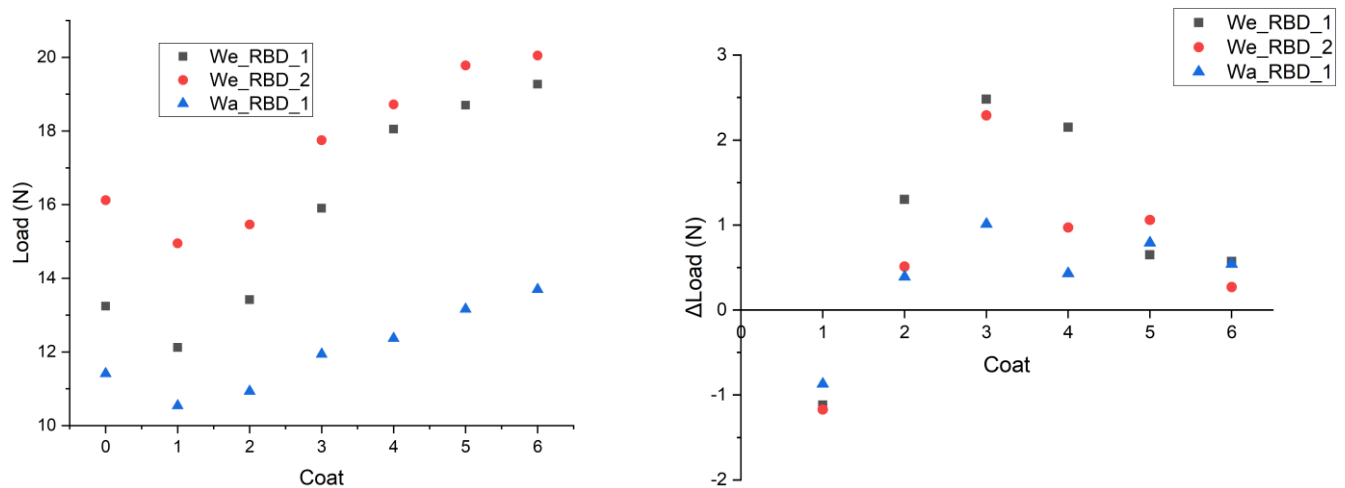


Figure 8-9: Left, the load exerted on 9F1 Irish Linen for each coat of 9701 Butyrate dope applied after 60 minutes. Right, the change in load exerted on 9F1 Irish Linen between each successive coat of dope applied

Number of Dope Coats	Load after each coat			Change in Load Between Each Coat		
	We_RBD_1	We_RBD_2	Wa_RBD_1	We_RBD_1	We_RBD_2	Wa_RBD_1
0	13.24	16.12	11.41	--	--	--
1	12.12	14.95	10.54	-1.12	-1.17	-0.87
2	13.42	15.46	10.93	1.3	0.51	0.39
3	15.9	17.75	11.94	2.48	2.29	1.01
4	18.05	18.72	12.37	2.15	0.97	0.43
5	18.7	19.78	13.16	0.65	1.06	0.79
6	19.27	20.05	13.7	0.57	0.27	0.54

Table 8-6: Load at the end of each coat and change in load between coats of Randolph 9701 Clear Butyrate dope on 9F1 Irish Linen

Although the tensile frame was programmed to remain at a constant extension some creep occurred, shown in Figure 8-10. All samples had an increase in strain when the first coat of dope was applied, after which the strain stabilised for several coats though with a slight downward trend. Midway during coat 3, the weft samples appear to have an increased strain response to the dope drying, with a sharp decrease in strain. With each subsequent application of dope there is an initial increase in strain, and then mid-way through the coat drying a decrease. The strain of the warp sample was considerably more stable compared to the weft, though increased response was observed during coats 5 and 6.

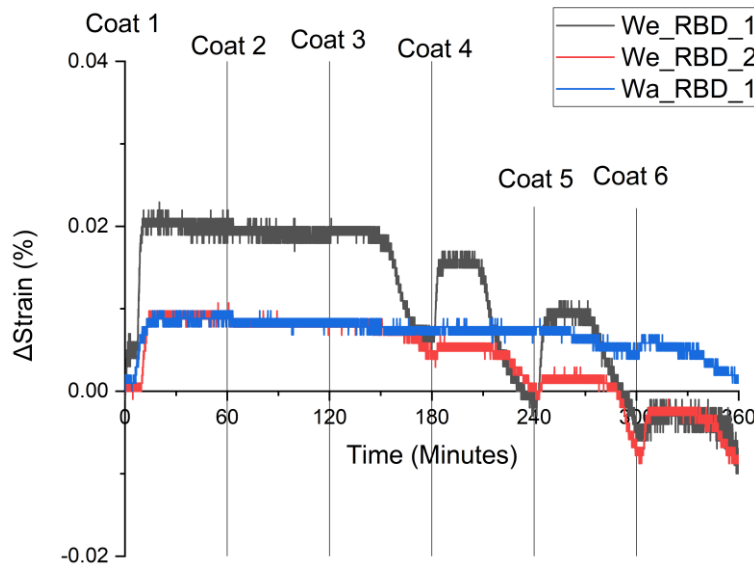


Figure 8-10: Change in strain of 9F1 Irish Linen held under tension as successive coats of dope were applied. At 360 minutes the two weft samples were sealed in different RH to continue drying (Figure 8-11). We_RBD_1 was placed in low RH conditions ($RH < 30\%$), while We_RBD_2 was placed in high RH conditions ($RH > 65\%$) created using the saturated salt solutions as discussed in 6.1.2, and the warp sample (Wa_RBD_1) was left to dry in ambient conditions. The load and displacement continued to be measured during this process, though measurements were cut short in the case of We_RBD_1 due to a power cut.

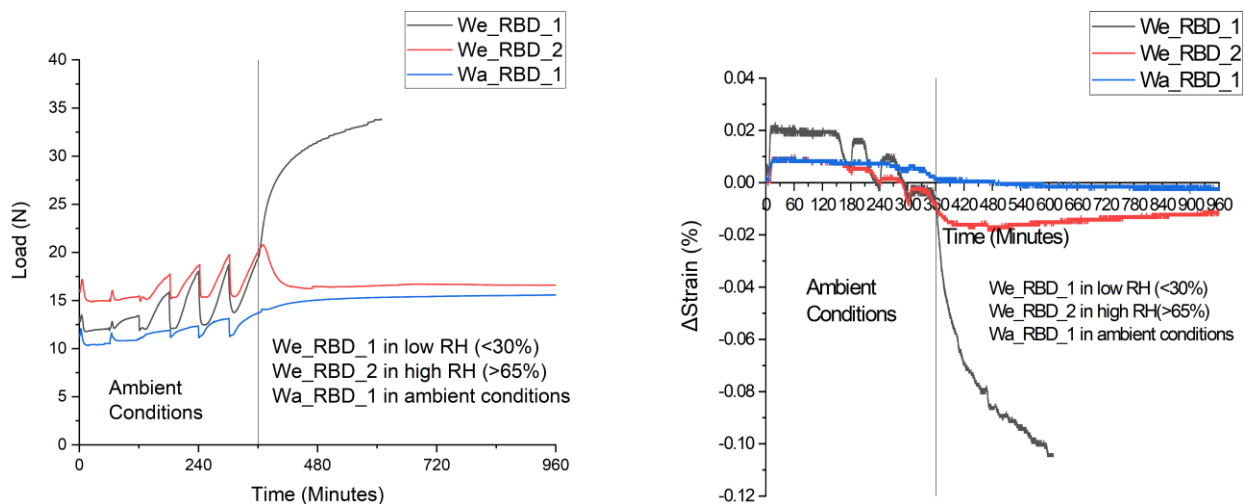


Figure 8-11: Left, the load exerted on 9F1 Irish Linen treated with 6 coats of 9701 Cellulose Butyrate dope and then placed into different RH conditions. Right, the strain of 9F1 Irish Linen treated with 6 coats of 9701 Cellulose Butyrate dope and then placed into different RH conditions

The load acting on the warp sample in ambient conditions continued to stabilise gradually, levelling off at approximately 15.5N. When placed into the different RH environments, however, the behaviour of the load

exerted on We_RBD_1 and We_RBD_2 changed considerably, despite having been relatively similar previously. The load acting on We_RBD_1 (RH<30%) began to increase at a faster rate, whilst the load exerted on We_RBD_2 (RH>65%) levelled off before decreasing to a stable level between 16.5 and 17N.

The load acting on We_RBD_2 and Wa_RBD_1 were both stable by 720 minutes with a change of less than 0.1N over the next four hours. The load on We_RBD_1 did appear to have begun levelling off, but the power cut unfortunately prevented completion of the experiment.

The strain measured during the same time period after the final coat of dope was applied is also shown in Figure 8-11. The strain of Wa_RBD_1 appears reasonably consistent though with a slight decreasing trend, whilst the strain of We_RBD_1, placed in low RH conditions at 360 minutes, continues to contract, the rate of which increases markedly at 360 minutes. There were signs of the rate of contraction slowing when the experiment was ended prematurely. We_RBD_2 continued to contract for a short time after being placed in the high RH environment before it began to relax and, after approximately one hour in this environment the strain began to increase at 420 minutes.

8.3.4. The Effect of Conservation Adhesives on the Load of 9F1 Irish Linen at Constant Extension

The different conservation adhesives all have a different effect on the load exerted on the fabric and Figure 8-12 shows how the load on fabric held at constant extension changed as the adhesives were applied.

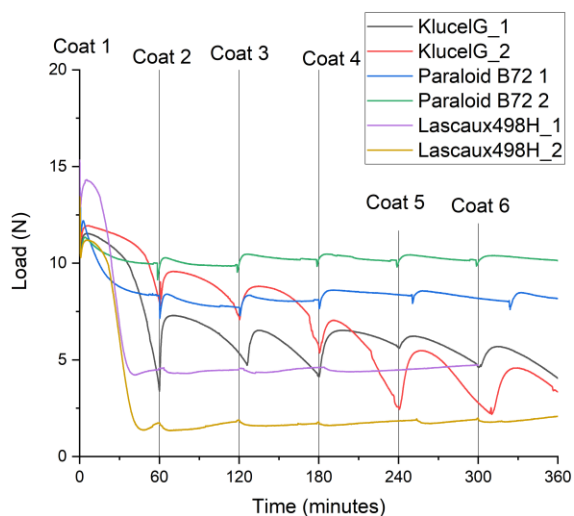


Figure 8-12: The Load exerted on 9F1 Irish Linen treated with 6 coats of different conservation adhesive against time. The adhesives used were Lascaux 498H, 5% Klucel G (w/v) in de-ionised water, 50% Paraloid B-72 (w/v) in 50:50 IMS and acetone.

Coat	Load at end of Coat (N)					
	KlucelG_1	KlucelG_2	Paraloid B72_1	Paraloid B72_2	Lascaux498H_1	Lascaux498H_2
0	13.87	14.04	14.08	12.94	15.34	13.44
1	8	3.39	8.33	10	4.58	1.75
2	7.22	4.75	7.71	9.92	4.55	1.89
3	5.68	4.15	8.11	10.18	4.62	1.78
4	2.58	5.63	8.34	10.15	4.5	1.89
5	2.25	4.65	8.06	10.16		1.99
6	2.83	4.05	8.13	10.15		2.07

Table 8-7: The load after 1 hour drying of each coat of conservation adhesive applied to 9F1 Irish Linen fabric held at constant extension.

From these results it can be seen that the adhesives have different drying mechanisms to that of the butyrate dope and, barring coat 1, tend to result in what appear relatively consistent loads being exerted on the fabric. On the first coat all samples experienced an increase in the load immediately after the adhesive was applied, after which the load decreased, the size and rate of which varied significantly between adhesives. Paraloid B72 and Lascaux 498H treated samples appeared to reach a relatively stable load before the next coat of dope, whilst for Klucel G treated samples the decrease in load did not levelling off.

From coat 2 on the behaviour of each adhesive type is different. In the case of Lascaux 498, each coat application causes a very slight increase and then decrease in the load immediately after application, before the load increased again very gradually. These changes are very small, however, in comparison to the decrease in load caused by coat 1.

Subsequent coats of Paraloid B72 resulted in an immediate drop in load and then increase within the first few minutes of application. After this the load gradually decreased before stabilising within the one hour drying period. This response was the most comparable to that of the dope, the major difference being there was no notable increase in load between coats as observed for the doped samples.

Klucel G caused the largest changes in load during each coat. Each coat of Klucel G after the first coat caused an immediate increase in load over approximately the first 10 to 15 minutes which gradually levelled off. This was followed by a decrease in the load which did not level off within the hour before application of the next coat.

Graph 15 shows the strain of the samples during the experiment. Although the frame was programmed to hold at a constant extension, as with doping samples there was some creep. The largest change in strain for all samples occurred during the period of the first coat. After the second coat the strain becomes stable and no longer varies, except in the case of sample KlucelG_2 where some further creep occurred throughout the experiment.

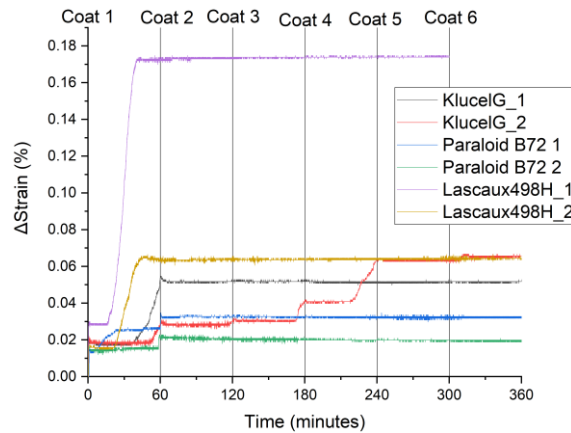


Figure 8-13: The strain of 9F1 Irish Linen as 6 coats of conservation adhesive were applied. The adhesives used were Lascaux 498H, 5% Klucel G (w/v) in de-ionised water, 50% Paraloid B-72 (w/v) in 50:50 IMS and acetone.

8.3.5. The Behaviour of Samples under loading at a constant rate of extension

The load-strain graphs of un-doped and doped 9F1 Irish Linen samples are shown in Figure 8-14. The warp direction in both the doped and undoped state is more extensible than in the weft, though supports a lower maximum load before failure begins to occur. There is also a change in behaviour between the doped and undoped samples. In the undoped samples the gradient of the initial portion of the load strain curve is increasing with increasing strain, whereas in the doped samples it decreases. The strain over which this gradient transition occurs is greater in the warp for both doped and undoped materials.

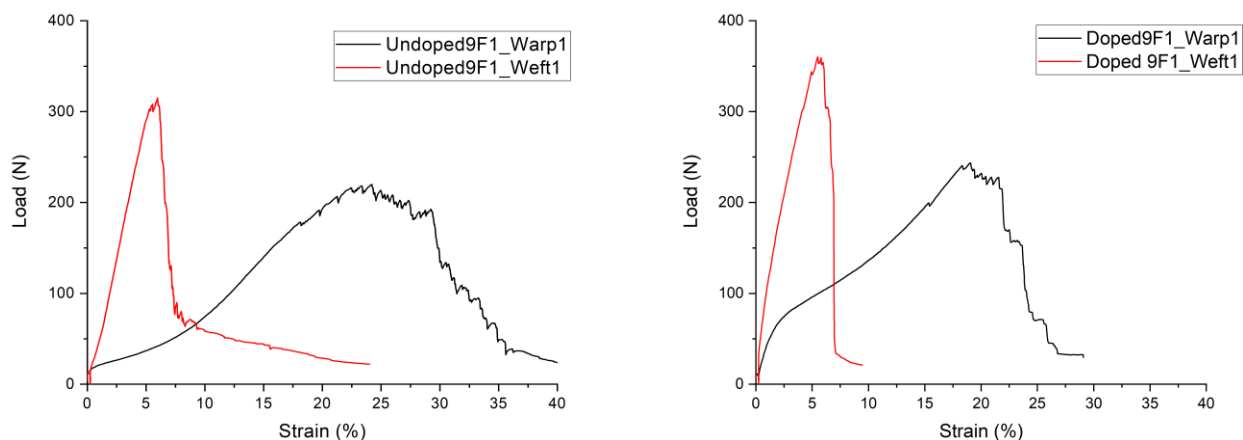


Figure 8-14: Top, load vs strain for 9F1 Irish linen in an undoped state and after treatment with 9701 Butyrate dope. Below, comparing the maximum load against strain of lab prepared and historic samples

The maximum tensile load against strain for both modern and historic materials have been shown in Figure 8-15 and values provided in Table 8-8 and Table 8-9. The maximum average load in both warp and weft can be seen to increase on doping, by 17% in the warp and 25% in the weft, whilst the weft sustained a greater maximum load than the warp, 31% greater when undoped, and 40% greater in the doped state. The average strain at maximum load was much greater in the warp than weft, being almost 5 times larger in the undoped state, and over 3 times greater once doped. On doping, the warp strain decreased by approximately 20%, while that of the weft increased by 10%.

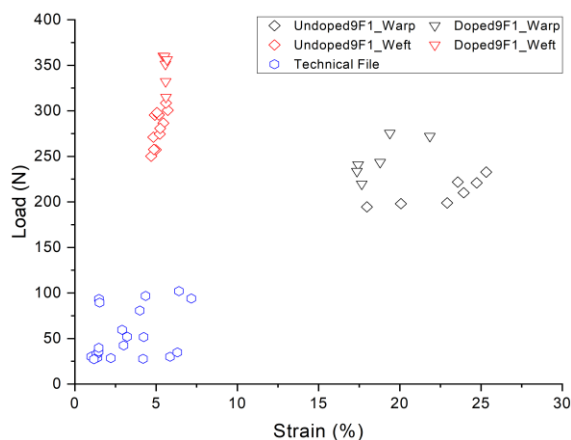


Figure 8-15: Maximum load against strain of modern lab materials and historic doped-fabric taken from the technical files at the Science Museum

The technical file materials sustained a much smaller maximum load than the modern doped-fabrics, approximately only 22% that of the warp direction and 16% that of the weft. This maximum load was also reached at a smaller strain on average, 18% that of modern doped-fabric in the warp and 60% that of the weft.

Differences in maximum load is observable in the X and Y directions of some technical file samples, in particular the JAP Monoplane where the Y direction maximum load was over 3 times that in the X direction. This indicates that the two fabric directions still had an influence, though this is not consistent across all the samples, such as the Se5a where the two directions cannot be differentiated between.

Undoped9F1_warp	Maximum Load (N)	Strain at maximum load (%)	Doped9F1_warp	Maximum Load (N)	Strain at maximum load (%)	Undoped9F1_Weft	Maximum Load (N)	Strain at maximum load (%)	Doped9F1_Weft	Maximum Load (N)	Strain at maximum load (%)
1	194.65	17.98	1	243.53	18.79	1	300.67	5.72	1	360.17	5.45
2	210.1	23.93	2	275.5	19.39	2	308.66	5.61	2	359.88	5.53
3	198.97	22.91	3	219.74	17.66	3	271.18	4.83	3	351.33	5.58
4	198.17	20.07	4	240.98	17.44	4	250.18	4.7	4	315	5.61
5	221.03	24.73	5	233.72	17.36	5	295.34	4.92	5	356.33	5.68
6	221.88	23.57	6	272.09	21.85	6	257.24	4.98	6	332.19	5.59
7	232.74	25.32				7	257.66	4.87			
						8	286.67	5.45			
						9	274.52	5.23			
						10	280.8	5.25			
						11	295.66	5.17			
						12	298.11	5.06			
Undoped_Warp Average	211.08 ±13.45	22.64 ±2.4	Doped_Warp Average	247.59 ±23.03	18.75 ±1.81	Undoped_Weft Average	277.28 ±12.26	5.09 ±0.20	Doped_Weft Average	345.82 ±19.24	5.57 ±0.08

Table 8-8: Values for maximum load and strain at the maximum load for modern doped-aircraft fabrics conditioned at 50%RH and tested to failure at a constant rate of extension. The dope used was Randolph 9701 Butyrate dope.

Technical File Samples	Maximum Load (N)	Strain at maximum load (%)
ANT_TF_X1	42.59	3.01
ANT_TF_X2	51.79	4.243
ANT_TF_Y1	27.4	5.864
ANT_TF_Y2	39.96	6.319
CBi_TF_X1	30.08	1.398
CBi_TF_X2	34.82	1.012
CBi_TF_Y1	59.66	1.491
CBi_TF_Y2	52.09	1.532
JAP_TF_X1	29.3	2.221
JAP_TF_X2	30.22	4.205
JAP_TF_Y1	94.14	2.912
JAP_TF_Y2	102.09	3.226
Se5_TF_X1	93.56	7.17
Se5_TF_X2	89.5	6.41
Se5_TF_Y1	96.92	4.359
Se5_TF_Y2	80.87	4.008
VV_TF_X1	28.64	1.332
VV_TF_X2	27.87	1.472
VV_TF_Y1	32.83	1.181
VV_TF_Y2	35.82	1.479
TF Average	54.01 ±12.98	3.32 ±0.93

Table 8-9 Values for maximum load and strain at the maximum load for technical file samples from the Science Museum conditioned at 50%RH

8.4. Discussion

The results of the two experiments to monitor the response of the 9F1 Irish Linen fabric to the application of the 9701 Randolph butyrate dope, one monitoring the strain of fabric panels using strain gauges and the second using a tensile frame to monitor load, are generally consistent with each other. An increase in load corresponds to a decrease in strain during the same experimental stages and vice versa, and this was observed over the experiment as a whole, and throughout each coating step of the experiments.

During coats 1 and 2, for example, a rapid decrease then increase in strain occurs when dope is first applied, which is reflected in the loading experiment by an immediate increase then decrease in load, while in later coats an immediate increase in strain on doping was matched by an immediate decrease in load on doping. A change in the dope drying mechanism therefore appears to take place over the course of the experiment as more coats of dope are applied, the alteration seeming to occur around coat 3 which marked the transition from 50/50 dope in acetone to undiluted dope. This change in behaviour around coat 3 was also observed in the size of load changes between coats, as the largest increase in load between coats occurred at coat 3 for all samples, and in the strain measurements where the behaviour of warp and weft began to diverge from coat 3 onwards.

The change in response may be due to a change in the interaction of the dope and fabric substrate as it becomes increasingly impregnated over successive coats (Figure 8-16). In coats 1 and 2, the initial decrease in strain and increase in load can be attributed to penetration of dope solvents into the fibres of the fabric yarns leading to a transverse swelling of them, which means yarns passing around each other must move through a greater crimp angle and, consequently, a greater distance. This effectively causes the yarns to shorten, increasing the load exerted on the sample and decreasing the strain measured in the panels.

The subsequent increase in strain and decrease in load then occurs as the dope solvents lubricate the fabric structure, enabling the yarns to re-organise themselves around each other at cross over points as friction is reduced. This lubrication of the fabric structure may also account for the creep observed in the early stages of coat 1 in the application of both dopes and conservation adhesives. The final decrease in strain and slight increase in load measured in some samples is then the result of the dope film forming within the yarn structures, and exerting a compressive force as the film formed.

From coat 3, however, when undiluted dope is used, the initial contraction and load increase becomes smaller, if not invisible, and the maximum strain reached decreases as the more viscous, undiluted dope does not penetrate the fabric structure to the same extent, and so the swelling and lubrication of the fabric structure does not occur or is much reduced. Instead, dope application results in an initial increase in the strain and decrease in load, which may be because the solvents of the freshly applied dope act on the previously formed dope films, softening and dissolving these layers, rather than penetrating the fabric substrate (Figure 8-17). At the same time, the greater volume of dope being applied in its undiluted form results in a thicker film and hence greater compressive forces as the dope film forms, resulting in the more notable changes in strain and load measured from coat 3 onwards.

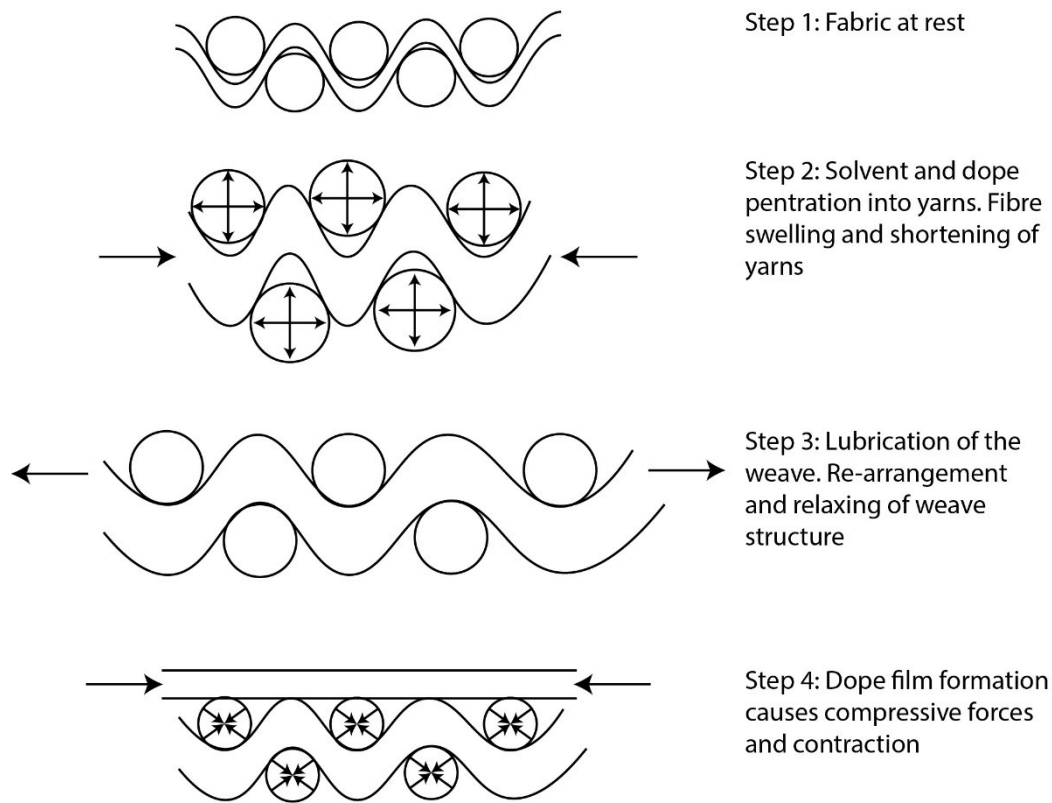


Figure 8-16: The effect of applying diluted dope on the strain of the fabric substrate during coats 1 and 2. Arrows indicate compression and extension of material.

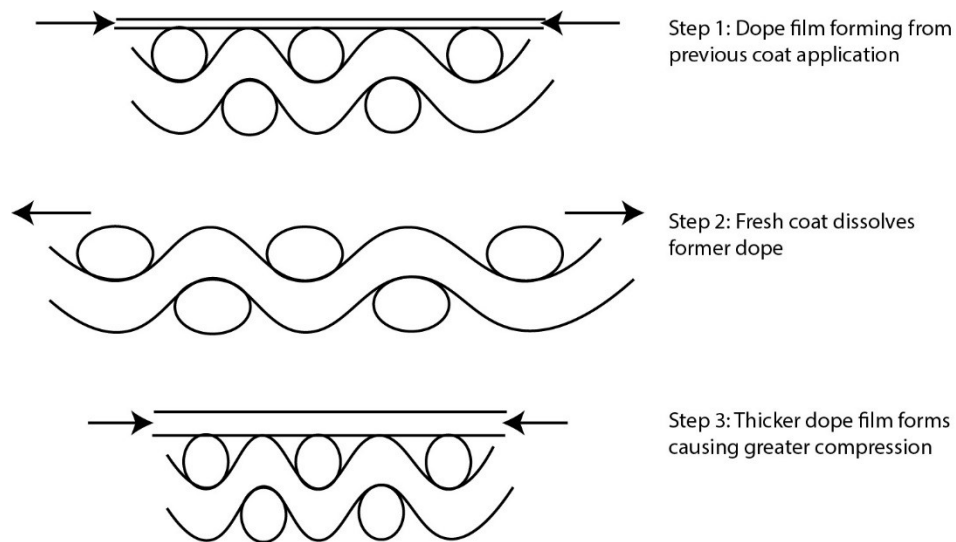


Figure 8-17: The effect of applying undiluted dope on the strain of the fabric substrate from coat 3 onwards. Arrows indicate compression and extension of material.

This has implications for use with historic materials, as it indicates that each application of dope in a conservation treatment is affecting the previous layers of dope below it, causing these to dissolve or soften. This could have significant consequences for a conservation repair using a doped-fabric patch, in that the interface between a historic and doped-fabric patch will be indistinguishable if the two layers combine, making removal of the patch far more ethically and practically challenging since it cannot be done without affecting the historic material. It also indicates that a doped-fabric patch will begin to exert a compressive force once the first coat of undiluted dope is applied, but that this may not be the case or the effect much reduced if only two coats of diluted dope are used.

Of further note is the comparison of behaviour in the warp and weft. When measuring strain, the weft direction of the fabric panels was found to undergo a greater overall compression than the warp by over twice as much, and in load measurements weft samples were also found to experience a greater load than the warp sample. When using the tensile frame, the compressive forces in the weft were strong enough as to move the frame jaws slightly closer together from coat 3 onwards and, although some change in strain was also measured by the warp sample, it was much smaller.

The difference in behaviour between the warp and weft directions could be attributable to a difference in crimp factor (chapter 2.2.1). During manufacturing, the warp must be raised and lowered to allow the weft to be passed through meaning that the warp usually has a greater crimp factor than the weft, and this can be seen in the SEM micrographs in which the weft passing around the warp ends appears almost straight in comparison to that of the warp moving around the weft yarn ends. This means that yarns in the weft direction are relatively straight in comparison to the warp yarns and so a greater component of the compressive force exerted by the weft yarns acts in the plane of the panel compared to that exerted by the warp yarns (Figure 8-18).

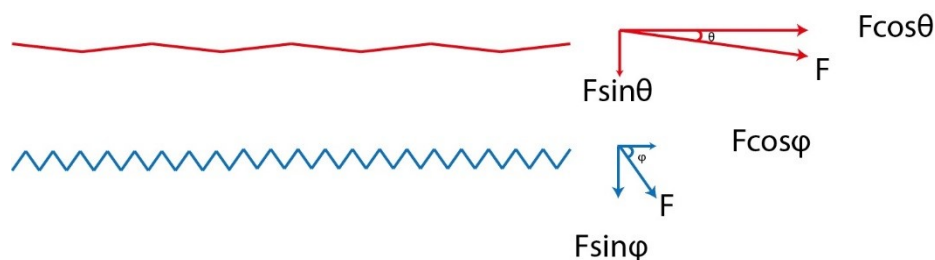


Figure 8-18: The potential effect of crimp in resolving forces within yarns due to formation of a dope film. N.B. the vectors shown are not to scale.

Other properties which may result in warp and weft differences are the yarn cross sectional shape and compression already exerted on the yarns in the two directions due to the weave, which may be related to several factors including the crimp factor, yarn selection and use of post-production treatments such as calendering. In the SEM micrographs, it was observed that the warp fibres are a more oval shape, compared to the rounder weft thread ends, though the effect of these other variations, and their relationship to the effects of crimp factor would require more extensive research to separate their individual effects.

This difference in crimp between warp and weft was also manifested in the differences between warp and weft samples tested to failure. The increasing gradient observed during the initial stages of the experiment in undoped samples is a result of crimp extension as the yarns are physically straightened, and was much more pronounced in the warp samples due to the extra crimp in this direction. As the crimp is removed from the undoped samples, the yarns become locked in place by the frictional forces acting at the cross over points, and once this process is complete there is then a relatively constant gradient as the cellulose molecules undergo extension before failure begins to occur.

On doping, however, the crimp effect is no longer evident, which likely happens because the weave has become locked into position by the dope film and so yarn extension due to removal of the crimp can no longer occur. Instead of an increasing gradient during the early stages of extension, there is instead a reasonably constant gradient which then begins to decrease, this behaviour being consistent with an initial elastic region before the yield point over which a transition from elastic to plastic deformation takes place.

It should be emphasised that only one type of aircraft fabric was tested, and so wider extrapolations to other fabrics, and their relationship between warp and weft when un-doped and doped, should be made with caution. Without further investigation into the relationship between the amount of crimp and the effect of dope, and tests to establish how different woven materials may behave, it would seem advisable in a conservation context to avoid the use of anisotropic woven materials for patching where the behaviour in the two directions, and the anisotropy of the material itself being treated, is unknown. Fabrics with little anisotropy or alternatives to woven fabrics such as Japanese papers, in which fibres are randomly oriented, would be potential starting points for further testing and consideration.

The effect of doping on crimp may further influence the average maximum load sustained and the strain at which maximum load occurs. The average values demonstrated that on doping the load bearing capability of the fabric increased, presumably as the dope film enables more even distribution of the load throughout the woven structure, rather than at fewer, localised points when undoped due to yarn cross over points being locked in

place. This locking of the weave also resulted in a stiffer material in the warp, with the maximum load occurring at lower extensions as crimp extension was no longer possible, though this was not consistent with the weft where a slight increase in the strain at maximum load occurred on doping.

The average maximum tensile load sustained by the modern samples was significantly greater than that of the historic materials, from the technical file, though this is not unexpected given the age of the historic materials of about 60 years old at least in most cases, and the various types of degradation that are likely to have occurred already discussed in chapter 5.2. It should reinforce the need to very carefully consider the appropriateness of doped-fabric patches as, were loading on an aircraft skin to increase it seems unlikely that failure of the modern doped-fabric patch would occur before the historic material. It may be suitable to investigate other materials with a more comparable tensile strength to that of the historic material for further testing, or an alternative option may be to investigate the bonding method and seek an adhesive or application method in which the bond between patch and historic material, rather than the material forming the patch itself, might fail first.

The difference in physical properties of historic and mechanical samples likely stems from chemical processes which have occurred in the historic samples, such as photo-oxidation, acid hydrolysis, deacetylation or denitrification depending upon the type of dope polymer and other further chemical reactions. These chemical alterations in polymeric materials were discussed in more detail in 5.2. Such chemical processes may have resulted in reducing the degree of polymerisation, the polymer weight and increased the crystallinity of historic samples, leading to more brittle materials which fail at lower loads.

Potential alternative adhesives available in place of dope have been considered in terms of the compressive force exerted on the 9F1 linen under constant extension in comparison to 9701 butyrate dope. None of the conservation adhesives caused an overall increase in load exerted on samples or resulted in a decrease in strain as with the dopes, but had quite the reverse effect resulting in a decrease in load and increase in strain. Indeed, barring the effects of coat 1 which as has been discussed is likely due to creep of the weave when first treated, the load and strain of samples treated with Paraloid B72 and Lascaux 498H remained reasonably consistent across all six coats.

One benefit of using these materials in place of dope, therefore, could be to reduce the risk of introducing further stress and strain into the historic material through patching, though further research into the strength of the bonds they might form, and hence how likely these might fail before the historic material, as well as their effect on previous doped layers, would be needed before they could be recommended with confidence.

The strain gauge and tensile frame results, moreover, do not support the hypothesis that dope contraction due to drying continues over a period of several years. Instead, the results indicate it is likely to take place primarily over the first 24 hours, as the load and strain stabilised during this period. The fluctuation of strain measured in the doped panels a few hours after the final coat was applied, however, indicates that other environmental factors, most likely RH (see chapter 9), were beginning to dominate the strain response of the material and so could hide further contraction occurring due to drying.

When the two weft samples were placed into high and low RH environments, one experienced an increase in load whilst the other a decrease, and so environmental conditions may influence the final compressive force acting on the material. In the case of the warp sample left in ambient conditions and the weft sample in low RH conditions, stabilisation of the load did occur approximately 6 hours after the final coat of dope was applied, indicating that the dope had finished drying and was no longer contracting.

It is possible that other longer-term processes, therefore, such as the migration of plasticisers, the effect of RH and the movement of the interior framework, could be of more significance and deserve more investigation in regard to the observed long-term shrinkage of doped-fabric. The doping of an entire aircraft, moreover, where much larger and more complex structures are involved may also result in a different behaviour than observed in these laboratory based experiments, for example were solvents to be trapped in the interior voids of the wing space they might continue softening the dope and thus result in long-term contraction of the fabric due to slowed evaporation.

8.5. Summary

The preceding chapter has shown that dope, when applied to a restrained fabric substrate under tension, caused a compressive force, resulting in an increase in load and a decrease in strain. The 9F1 Irish Linen tested was anisotropic, moreover, with the weft undergoing a greater compression and experiencing a greater compressive force than the warp. The overall change in load and strain appears related to the number of coats and formulation of dope with several preliminary coats of diluted dope resulting in relatively little overall change in load or strain compared to the use of undiluted dope in subsequent coats.

The application of conservation adhesives was also shown to affect the load exerted on a fabric substrate restrained under tension but in a very different way to dope, causing an overall drop in load and, in the case of Paraloid B72 and Lascaux 498H relatively little change to the load after the initial application.

Historic technical file samples were also shown to bear a much smaller maximum load compared to modern doped-fabric samples, suggesting any further failure would likely occur in the historic material rather than the patch, unless the bond could be designed to fail. For these reasons it is advisable that alternatives to doped fabric should be investigated, both in terms of the materials selected and the methods employed for securing any patch in place if used.

9. The Response of Doped-Fabrics to Changes in Relative Humidity

9.1. Introduction

As discussed in the literature review, the response of materials to changes in Relative Humidity (RH) has been identified by the conservation profession as a potential contributor to the deterioration and failure of cellulosic and other organic materials (chapter 5). Paintings conservation studies, for example, have shown that for a painted canvas held under tension an increase in RH will generally result in a decrease in load due to relaxation of proteinaceous sizing layers, such as rabbit skin glue, whilst a decrease in RH causes a contraction of the same layer leading to an increase in load.

Anecdotal and historic reports indicate that, despite being impregnated with very different chemical compounds compared to canvas paintings, moisture influences the strain of aircraft fabric in a similar manner (chapter 2.2), as increased RH was found to reduce the tautness of doped-fabrics and research into doped-fabric invested heavily in searching for dopes that would remain taut during and after repeated exposure to high RH conditions. That the aircraft on display in *Flight* respond to fluctuations in the RH of the gallery environment seems likely, therefore, but this mechanism requires investigation to understand the extent to which such processes may still occur given the aging of the objects, and how their current response might compare to the modern materials being used to patch them.

9.2. Experimental

9.2.1. Strain Gauge Panels

Panels of 9F1 Irish Linen aircraft fabric were prepared as described in chapter 6. The results of the strain measured during Steps 1 and 3 of the doped-fabric panel preparation process will be presented here. During step 1 the un-doped fabric panels were subjected to RH cycling, and during step 3 the doped-fabric panels were subjected to RH cycling. Strain gauge readings have been zeroed to the beginning of step 1 after the panels were conditioned at low RH conditions in the humidity chamber.

Only panels prepared using configuration 1 will be discussed here as these were exposed to more RH cycles than those made using configuration 2, and because the 4 Con1 type panels were all cycled together it enables comparison of like with like between the panels.

9.2.2. In-Situ Strain Measurements on Gallery

Type EA-06-250AE-350 resistance strain gauges were attached to the doped-fabric skins of the JAP Harding Monoplane and Vickers Vimy on *Flight* as discussed in 6.2. This was carried out to directly monitor the strain of the original material within the display context.

Only the response of strain measured on the JAP Harding Monoplane, Vickers Vimy upper port wing and Vickers Vimy cockpit area will be discussed here because these are areas in which the historic material was undamaged. The results from the other gauge areas monitored around torn areas will be presented in the next chapter relating to investigations into the effects of tears and patching. The location and designation of monitored areas are provided in Table 9-1 and Figure 9-1.

Aircraft	Location	Gauge designation	Area Patched (Y/N)
JAP Harding Monoplane	Starboard wing upper surface exterior	JAP_Ext_X JAP_Ext_Y	N
JAP Harding Monoplane	Starboard wing upper surface interior	JAP_Int_X	N
JAP Harding Monoplane	Unattached control	JAP_Con	N
Vickers Vimy	Upper port wing exterior	VV_UPW_X VV_UPW_Y	N
Vickers Vimy	Fuselage, cockpit area interior	VV_Cp_X VV_Cp_Y	N

Table 9-1: Locations monitored on Flight to assess response of undamaged historic fabric response to gallery environmental conditions

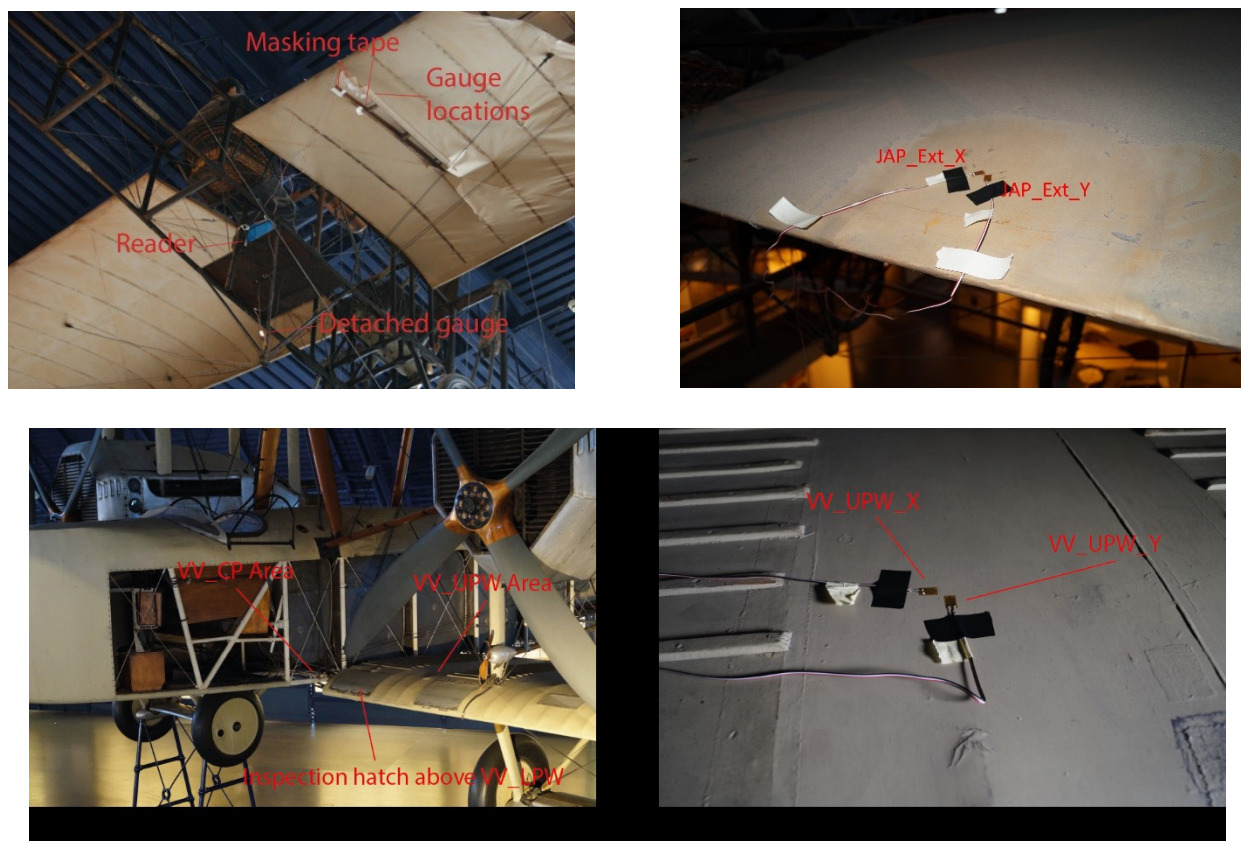


Figure 9-1: Location of strain gauges used to monitor undamaged areas of doped Fabric on *Flight*. Top the JAP Monoplane, bottom Vickers Vimy

9.2.3. RH Cycling for Fabric Restrained at a Constant Extension

Samples of un-doped 9F1 Irish Linen measuring 70x30mm, 9F1 Irish Linen doped with Randolph 9701 Butyrate dope measuring 30x15mm, and historic samples cut from the technical files and *in-situ* gallery materials measuring 30x15mm were mounted in the jaws of a Gatan M2000E 2kN tensile frame between two pieces of archival card lining the jaws. A list of samples is provided in Table 9-2.

Once mounted the samples were extended at a constant rate of 0.4mm/min until a load of 20N was measured when they were restrained at constant extension. The samples were then covered with a Stewart Box to create a sealed environment, and the RH lowered to below 30% by introducing a saturated potassium acetate salt solution. Samples were left a minimum of 12 hours overnight to allow the load to stabilise. A wireless Hanwell ml4000 temperature and humidity data logger was sealed within the chamber to monitor environmental conditions.

Once the load on the samples was stable, the RH was cycled by placing a saturated sodium chloride salt solution into the box to create a high RH environment (>65%), and a low RH by replacing it with the potassium acetate saturated salt solution. Each RH cycle occurred over a 2-hour period with one cycle consisting of two phases;

- Phase 1: Raising the RH for 1 hour, ensuring it went over 65%
- Phase 2: Lowering the RH for 1 hour, ensuring it went below 30%

Two RH cycles were completed, after which the samples were left to acclimatise to low RH conditions until the load stabilised, when they were tested to failure by opening the jaws at a constant extension rate of 0.04mm/min.

Sample Type	Source	Dimension (mm)	Number of Samples
Undoped9F1_Warp	Undoped 9F1 Irish Linen	70x15	1
Undoped9F1_Weft	Undoped 9F1 Irish Linen	70x15	1
Doped9F1_Warp	Lab prepared doped-fabric panel	30x15	3
Doped9F1_Weft	Lab prepared doped-fabric panel	30x15	4
Gallery Sample X Direction	Antoinette Monoplane JAP Monoplane Pterodactyl Supermarine S6B Vickers Vimy	30x15	5
Gallery Sample Y Direction	Antoinette Monoplane JAP Monoplane Pterodactyl Supermarine S6B Vickers Vimy	30x15	5
Technical File X Direction	Cody Bi-Plane JAP Monoplane Se5a Vickers Vimy	30x15	4
Technical File Y Direction	Cody Bi-Plane JAP Monoplane Se5a Vickers Vimy	30x15	4

Table 9-2: List of samples used to test response of material to RH cycles at constant extension

9.3. Results

9.3.1. The Strain Response of Fabric Panel to Cycling Relative Humidity

Before setting up fabric panels in the humidity chamber an unattached strain gauge was exposed to cycling RH conditions to check the response of the gauges and against which to compare the results of gauges adhered to a test material (Figure 9-2). The strain gauge did respond to changes in RH, presumably due to absorption and desorption of moisture by the polymer backing, and had a maximum strain response of $\pm 0.03\%$ between 25 and 72.5% RH. No time lag between the change in RH and response of the gauge was observed and a linear line of best fit was used to calculate a rate of strain response of 0.0006% per 1% RH change between approximately 25-72.5%RH. A summary of the rate of response of the different materials in the various experiments is provided in Table 9-3, page 234.

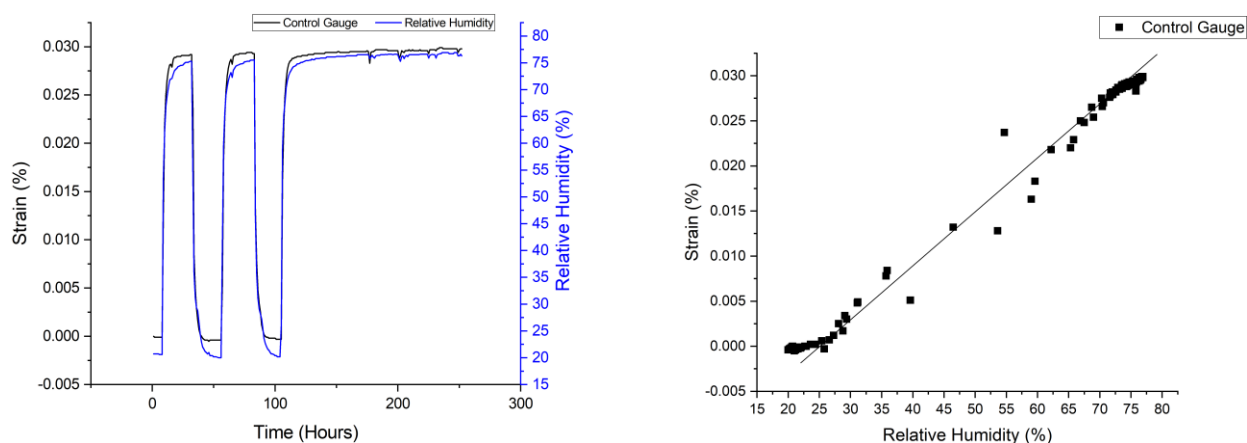


Figure 9-2: The change in strain of an unbonded strain gauge and Relative Humidity against time.

The strain of the doped-fabric panels during steps 1, 2 and 3 of the fabric panel preparation process is shown in Figure 9-3 and Figure 9-4. The strain has been zeroed to the beginning of step 1, and this section will provide a comparison of behaviour in steps 1 and 3. The strain response of the fabric during step 2, the application of dope, has already been discussed in the previous chapter 8.

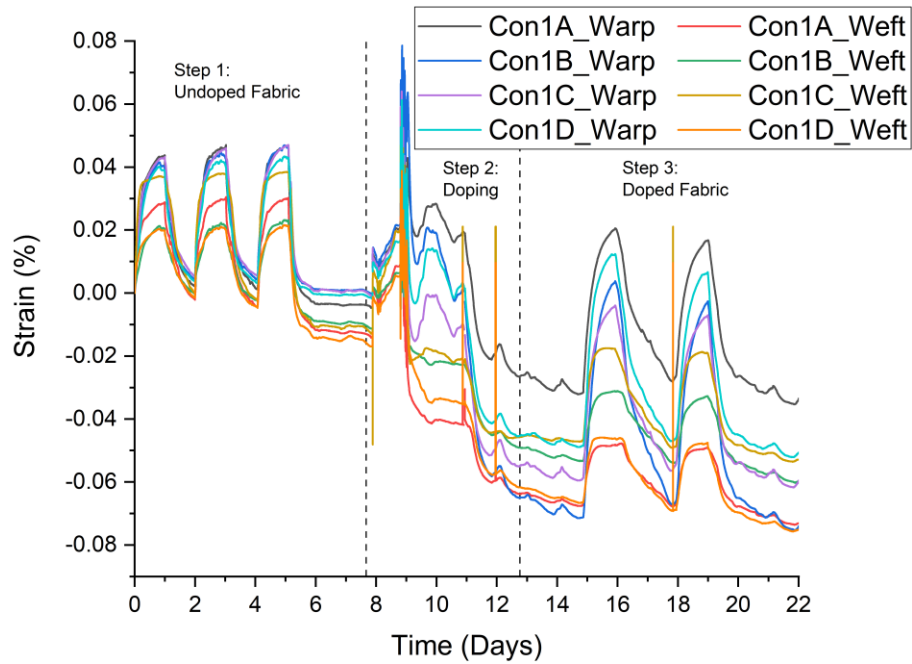


Figure 9-3: Strain of doped-fabric panels during the 3 experimental phases: 1) RH cycling of the undoped fabric, 2) the application of dope, 3) RH cycling of the doped-fabric panels, against time

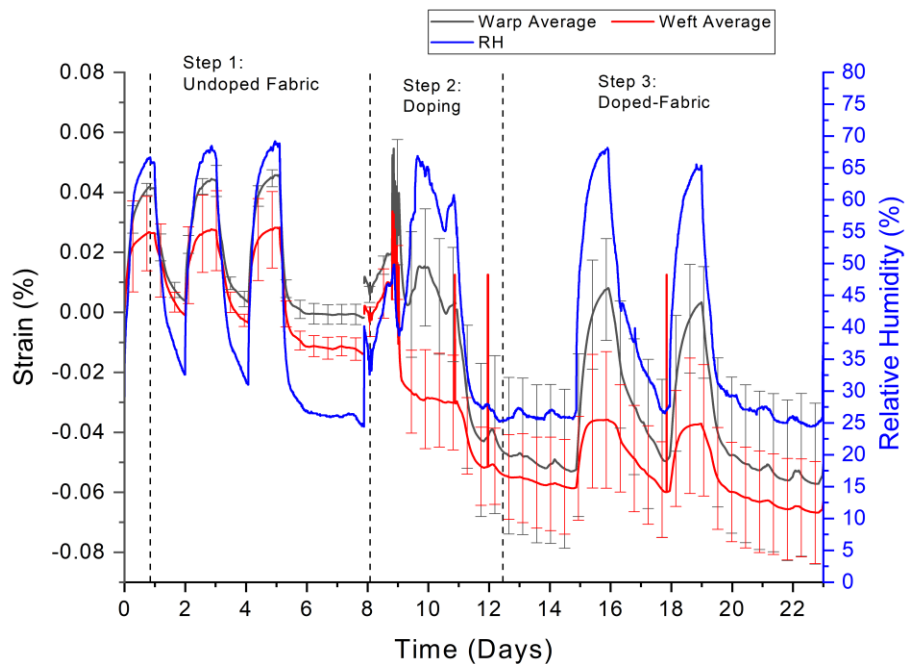


Figure 9-4 : Average Strain of doped-fabric panels during the 3 experimental phases: 1) RH cycling of the undoped fabric, 2) the application of dope, 3) RH cycling of the doped-fabric panels and the Relative Humidity over the same period against time. (Error bars represent a 95% confidence interval based on a t-distribution).

The average strain of un-doped 9F1 Irish Linen fabric in the warp and weft direction against time and against RH over that same period is shown Figure 9-5. An increase in RH leads to an increase in strain and a decrease in RH causes a decrease in strain, and the strain response of the fabric appears to be near instantaneous, with no detectable delay between a change in the RH and the fabric response. Over the course of the three cycles the strain of the weft decreased compared to the starting strain by approximately 0.01%, whilst that of the warp increased very slightly by approximately 0.002%. The change in strain between 30% and 65% RH during cycles 2 and 3 is approximately 0.04% in the warp and 0.03% in the weft.

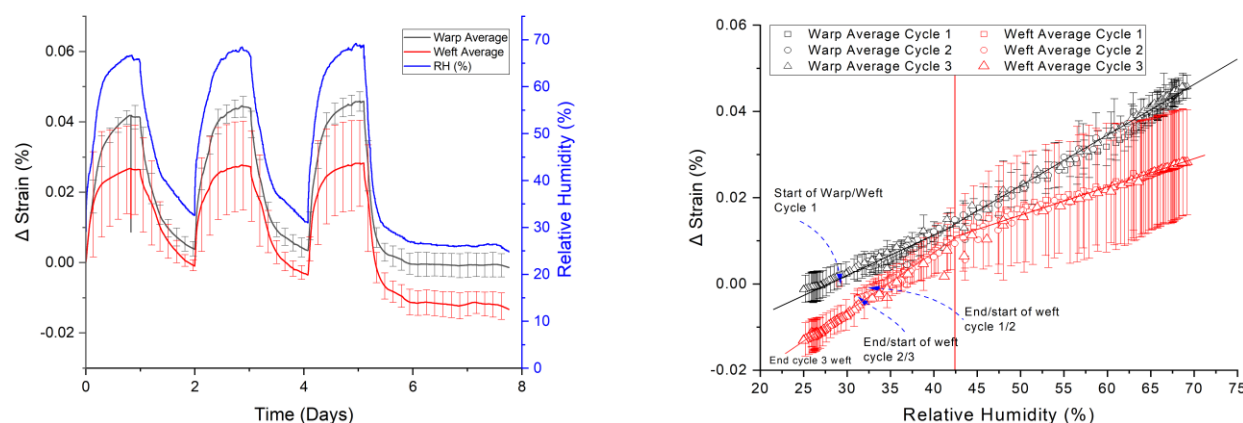


Figure 9-5: Response of undoped 9F1 Irish Linen to changes in Relative Humidity over time (Error bars represent a 95% confidence interval based on a t-distribution).

A change in the response of strain to RH occurred around 42.5% RH in both the warp and weft. Below 42.5 the weft had a greater response to changes in RH than the warp, but above 42.5% this was reversed as the response rate of the warp increased slightly and that of the weft decreased markedly (Table 9-3). The increased variability of the weft direction above 42.5% is also notable.

The average change in strain of the 9F1 Irish Linen after doping against time, and the change in strain against RH in the same period is shown in Figure 9-6. As with the un-doped fabric, a rise in RH leads to a rise in strain and a decrease in RH leads to a decrease in strain. A hysteresis effect not seen in the undoped fabric is apparent during the RH cycling of the doped panels which indicates that the effect of RH is not identical when increasing and decreasing RH. Cycling of the RH does not alter the overall strain of the doped-fabric in the warp and weft direction as it returns to a similar level after each cycling event. As RH increases, the variability between the panels in the warp direction becomes much greater than that seen in the weft, whilst at lower RH levels there is relatively little variability in either the warp or weft direction.

A plateauing of the weft values above 60% indicate that in this direction a change in strain of approximately $\pm 0.02\%$ between 30-65%RH, unless a further mechanism occurs at a higher RH than was achieved during these experiments which causes additional strain. No such plateau occurs in the warp direction, indicating that a higher RH could still give rise to further increases in strain. On increasing RH the strain increased by approximately 0.05% on average between 30-65%RH. The rate of response of the warp to RH between 35-55%RH, was found to be 1.8 times greater than that of the weft response.

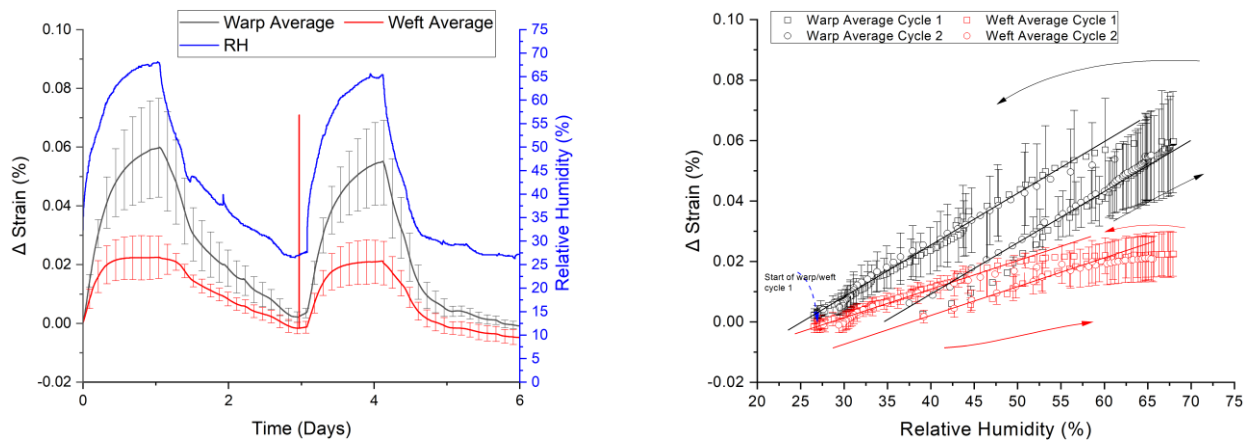


Figure 9-6: Response of 9F1 Irish Linen doped with Randolph 9701 Cellulose Acetate Butyrate dope to changes in Relative Humidity over time (Error bars represent a 95% confidence interval based on a t-distribution).

9.3.2. In-Situ Monitoring of Strain in Historic Aircraft on Display

The strain measurements of the doped-fabric aircraft monitored *in-situ* are shown in Figure 9-7. The response is comparable to that of the fabric panels in that an increase in RH results in a rise in strain and a decrease in RH a decrease in strain. There is no hysteresis visible, indicating a similar response occurred both when RH was increasing and decreasing. The strain response of the aircraft to changes in RH is rapid, with no detectable lag time between a change in RH and the strain.

The gallery control behaved in a comparable manner to that used in the controlled lab cycling experiment and the response of the JAP Monoplane and Vickers Vimy fuselage area were both approximately twice that of the lab control gauge. The rate at which the JAP Monoplane and Vickers Vimy fuselage fabric responded to changes in RH are comparable with each other, and neither showed signs of plateauing at either the high or low RH bounds, changing by approximately $\pm 0.025\%$ between 25 and 45%RH. The exterior port wing of the Vickers Vimy was the only location where a slower strain response than the lab control was recorded, and the response of the

port wing also appears to plateau as RH decreases below approximately 25%, suggesting that it was approaching or had reached a minimum strain.

The two directions of the Vickers Vimy fuselage responded in a very similar manner, with little to distinguish their response, whilst on the JAP Monoplane the X direction had a 16% greater response to changes in RH than the Y. The biggest difference in response between the X and Y directions was that of the Vickers Vimy Port wing exterior above 25%RH, when the X direction responded approximately twice as much to the same change in RH as the Y direction.

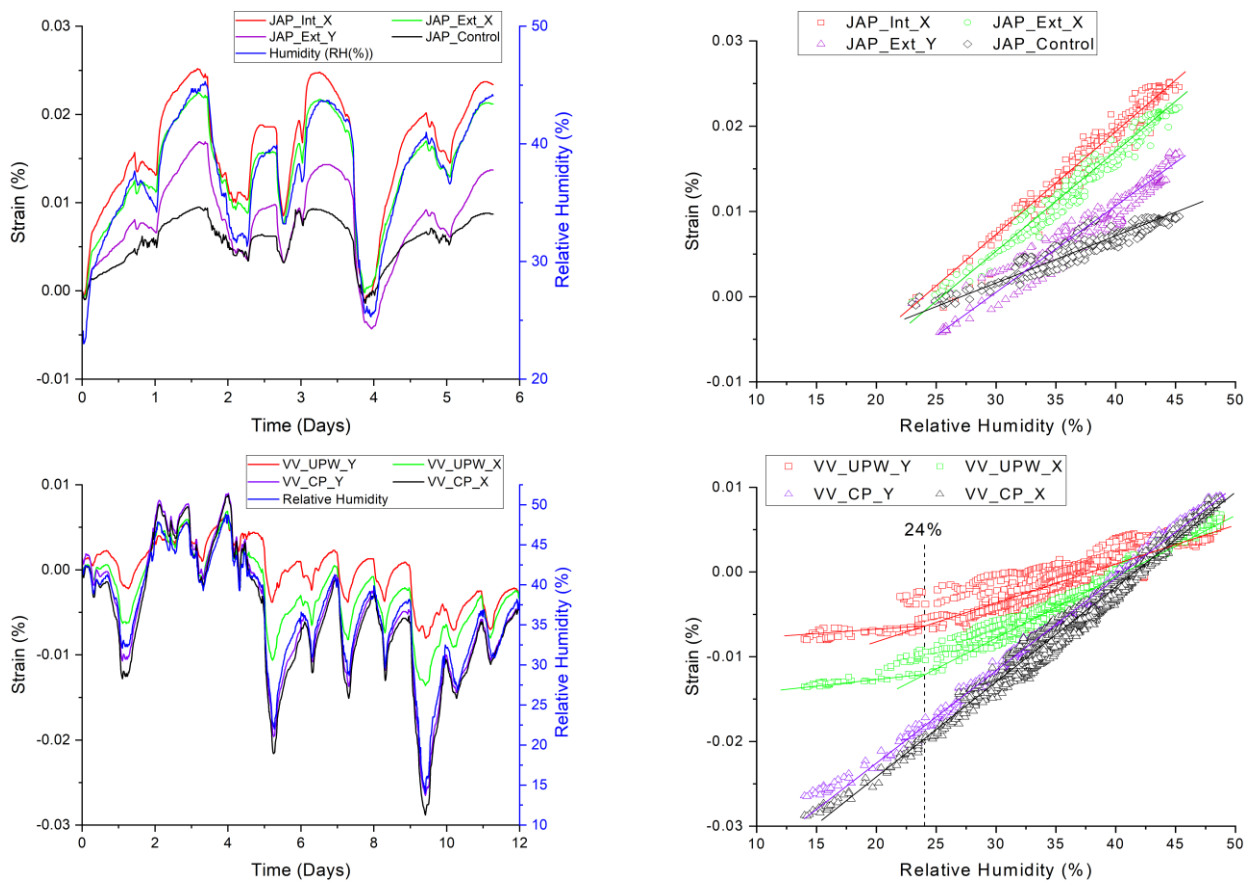


Figure 9-7: Strain measurements made *in-situ* on Flight of the JAP Harding Monoplane (top) and Vickers Vimy fuselage doped-fabric surfaces

RH Range (%)	Sample Type	Strain Response Rate (strain per RH)	Ratio to Lab Control Gauge
<42.5	Undoped9F1_warp	9.26E-04	1.55
<42.5	Undoped9F1_weft	1.39E-03	2.32
>42.5	Undoped9F1_warp	1.18E-03	1.97
>42.5	Undoped9F1_weft	6.56E-04	1.10
30-60	Doped9F1_warp	1.71E-03	2.86
30-60	Doped9F1_weft	9.50E-04	1.59
15-45	Vimy_CP_X	1.12E-03	1.87
15-45	Vimy_CP_Y	1.09E-03	1.82
25-45	Vimy_UPW_X	7.25E-04	1.21
25-45	Vimy_UPW_Y	4.58E-04	0.76
<25	Vimy_UPW_X	1.56E-04	0.26
<25	Vimy_UPW_Y	9.99E-05	0.17
25-45	JAP_Ext_X	1.17E-03	1.96
25-45	JAP_Ext_Y	1.02E-03	1.70
25-45	JAP_Int_X	1.21E-03	2.02
25-70	Lab Control Gauge	5.99E-04	1.00
25-45	Gallery Control Gauge	5.84E-04	0.98

*Table 9-3: Rate of change in strain to fluctuations in RH of modern fabric and doped-fabric panels, and historic aircraft fabrics on display in *Flight* at the Science Museum*

9.3.3. RH Cycling for Fabric Restrained at Constant Extension

In all sample types tested, whether modern or historic, doped or un-doped, an increase in RH led to a decrease in load which showed signs of stabilising with time (Figure 9-8). The reverse occurred when the RH was decreased, when an overall increase in the load was measured. The response of the samples appears to have been almost immediate and the behaviour of modern doped samples and historic samples taken from the museum technical files and *Flight* are very similar.

The undoped 9F1 Irish linen fabric samples responded to the change in RH differently to the doped modern and historic materials in the immediate period after the saturated salts were exchanged and the RH changed. When RH began to increase there was an initial increase in the load before it began to decrease, and vice versa when RH began to decrease which can be seen on the graph for sample Undoped9F1_Weft1 as large 'bumps' in the graph.

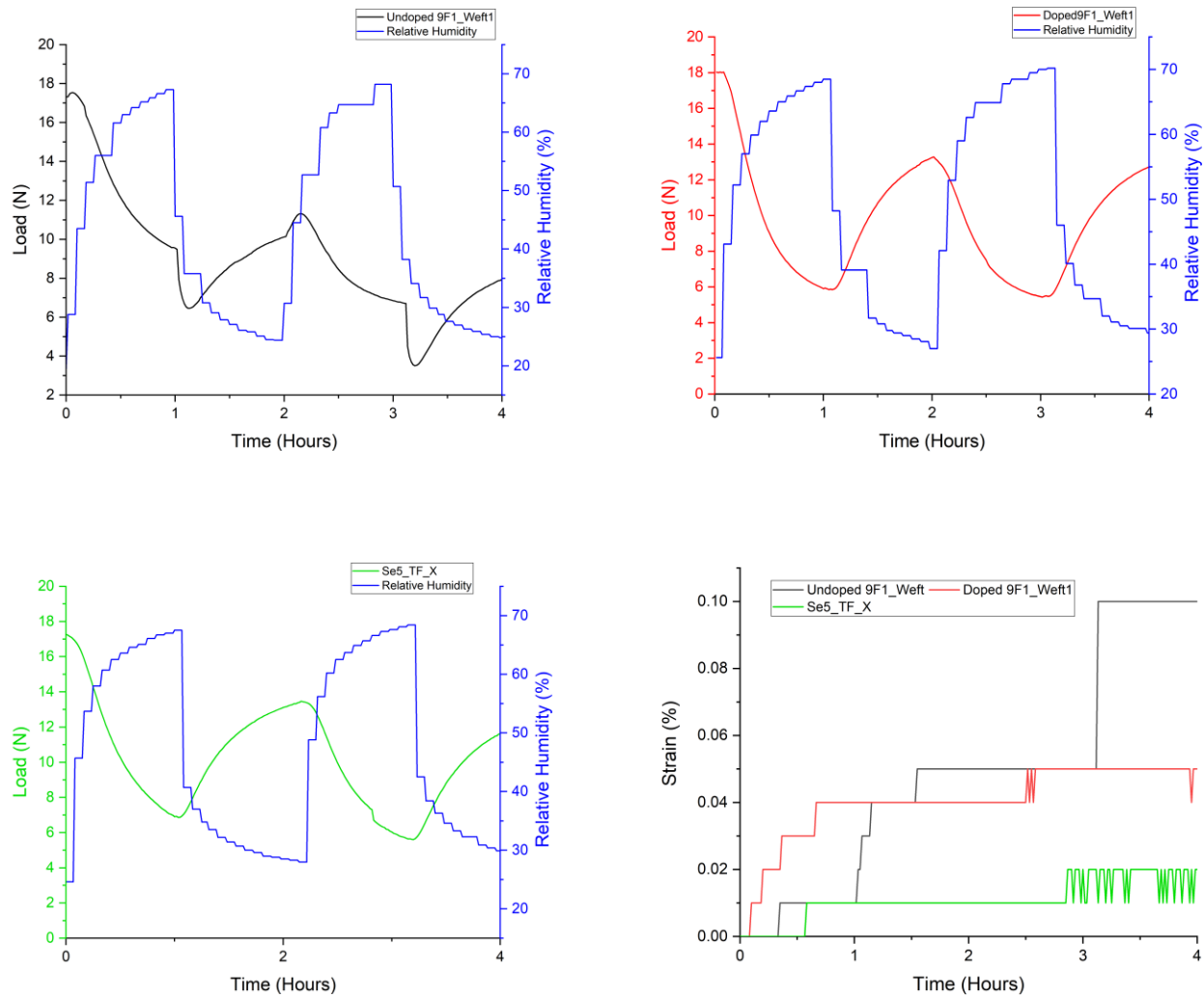


Figure 9-8: The response of load acting on undoped 9F1Irish linen, a piece of 9F1 Irish Linen doped with Randolph 9701 Butyrate dope and material from the JAP Monoplane on display in Flight to changes in Relative Humidity and the strain of the samples during the same period of time.

The proportion of the initial load sustained at the end of each stage of the RH cycles also demonstrates a difference between the behaviour of doped and un-doped materials (Figure 9-9). The load sustained by samples of un-doped linen dropped to approximately 50% after the first step of cycle 1 (hour 1), after which the RH decrease during step 2 resulted in little overall increase in the load. There was then a further drop in the load when the RH was increased for a second time between hours 2 and 3, to approximately 30% of the starting load, and a load regain of approximately 10% on the final decrease in RH.

In the case of modern doped and historic samples, the first increase in RH caused a drop in RH to anywhere below approximately 50% of the initial load. The subsequent RH decrease, however, resulted in greater regains

in load compared to that of the un-doped samples of between approximately 30-40%, and this was repeated in cycle 2.

A difference in behaviour between warp and weft is also seen in the modern samples where the warp tends to experience a larger decrease in the load sustained in both the un-doped and doped state. This is not true across all samples, however, as Doped9F1_Warp 3 behaved in an identical manner to doped weft samples.

In all samples some creep occurred during the first hour of the cycling, when RH was first increased. Beyond the first hour, however, the doped and historic samples ceased to creep significantly, though further creep was observed in the modern, undoped 9F1 linen samples (Figure 9-8).

In the case of two historic materials, the Cody Bi-Plane and Vickers Vimy, the load exerted became a negative value, indicating the material experienced a compressive force.

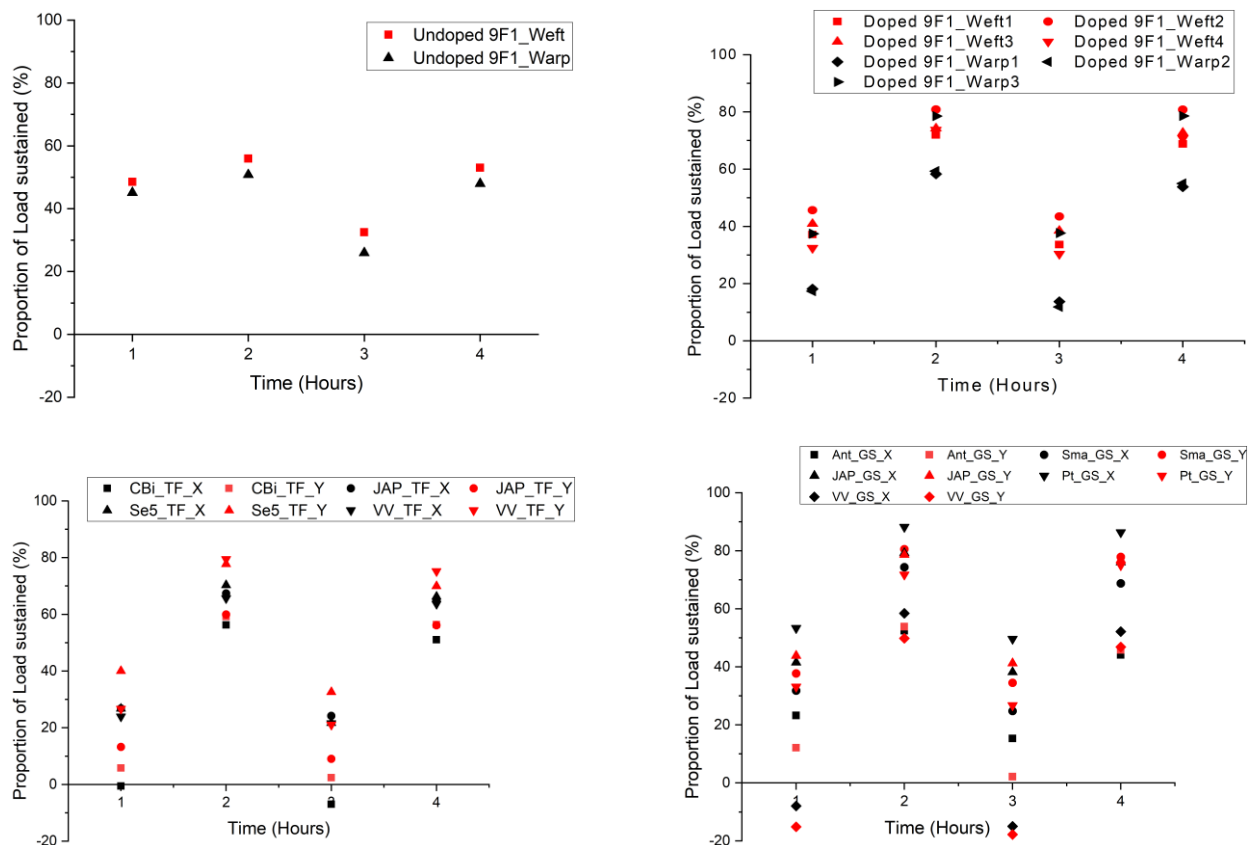


Figure 9-9: The proportion of initial load sustained during RH cycling of on undoped 9F1Irish linen 9F1 Irish Linen doped with Randolph 9701 Butyrate dope, material from the Science Museum technical file and sampled from aircraft on display in Flight.

The results of the final stage of this experiment, when the material was extended to failure, is consistent with the previous tensile testing to failure using 50%RH conditioned samples in that the historic samples support a smaller maximum load than modern samples before failure occurs (Figure 9-10, Table 9-4 and Table 9-5). Also consistent is a comparison of warp and weft behaviours and the effect of doping in which the warp is more extensible but fails at lower loads than the weft.

There appears to be a significant overlap between the historic materials sampled from *Flight* and the technical files. The average maximum load of the technical file samples, and the results of the modern materials also appears to be somewhat higher than that measured in the samples conditioned to 50% RH, though the alteration of test conditions, both in terms of lowering the RH conditions and introducing the extra cycling stages, could account for this difference.

Lab Prepared Samples	Maximum Load (N)	Strain at Maximum Load (%)
Undoped 9F1_Warp	227.26	24.27
Undoped9F1_Weft	294	5.322
Doped9F1_Warp1	339.69	16.111
Doped9F1_Warp2	326.47	16.689
Doped9F1_Warp3	270.01	12.967
Doped9F1_Weft1	455.84	6.572
Doped9F1_Weft2	447.79	7.701
Doped9F1_Weft3	420.81	6.013
Doped9F1_Weft4	488.61	5.79

Table 9-4: Maximum load and strain at maximum load of modern lab prepared samples tested to tensile failure after RH cycling

Technical File Material	Load (N)	Strain (%)	Gallery Material	Load (N)	Strain (%)
Cbi_TF_X	61.98	2.54	Ant_GS_X	61.99	1.01
Cbi_TF_Y	31.26	4.97	Ant_GS_Y	50.22	1.11
JAP_TF_X	26.83	1.69	JAP_GS_X	103.72	1.90
JAP_TF_Y	124.47	3.43	JAP_GS_Y	135.90	1.86
Se5_TF_X	93.10	4.35	Pt_GS_X	64.41	1.84
Se5_TF_Y	100.94	7.62	Pt_GS_Y	67.12	4.13
TF_VV_X	25.47	3.31	Sma_GS_X	98.03	2.31
TF_VV_Y	31.76	1.69	SMA_GS_Y	73.25	1.77
TF Average	61.98 ±32.87	3.70 ±1.64	VV_GS_X	82.06	2.68
			VV_GS_Y	98.87	2.70
			GS Average	83.56 ±18.33	2.13 ±0.64

Table 9-5: Maximum load and strain at maximum load of technical file and gallery samples tested to tensile failure after RH cycling

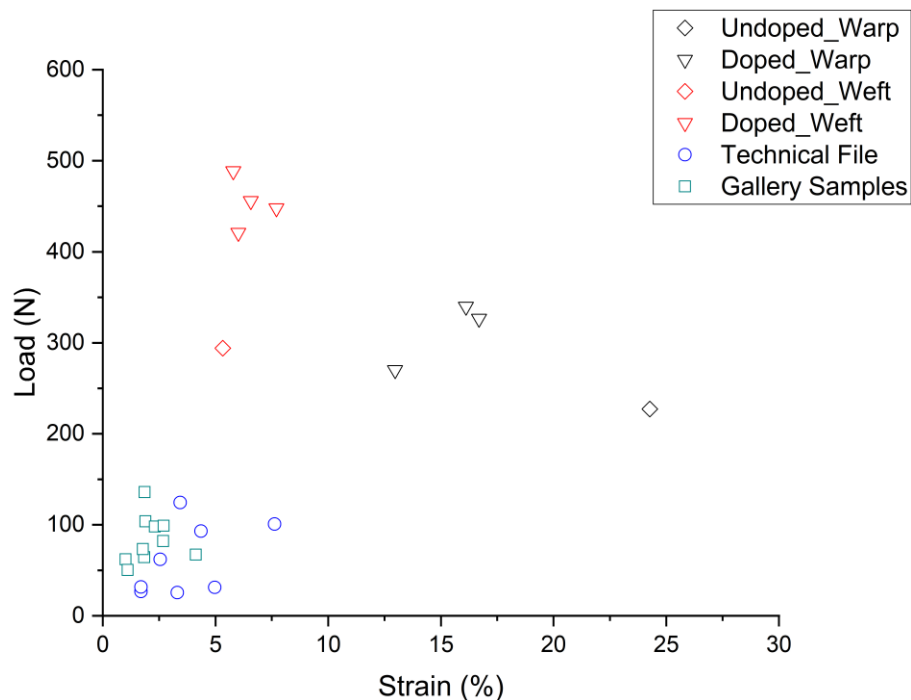


Figure 9-10: Maximum load against strain for samples tested to failure under tensile loading after RH cycling

9.4. Discussion

The results of the strain gauge experiments demonstrate a relationship between strain and RH in the laboratory fabric panels when both undoped and then doped, and for the *in-situ* historic aircraft on display. In both the modern 9F1 Irish Linen and historic material an increase in RH was related to an overall increase in strain, and a decrease in RH a decrease in strain. A relationship between load and RH was also observed during the RH cycling of samples held at constant extension using the tensile frame. For both historic and modern samples an increase in RH was found to coincide with an overall decrease in load, and a decrease in RH an increase in load. This is the inverse of the relationship shown in the strain gauge experiments, as is to be expected given the inverse relationship between load and strain.

In the case of doped samples, the effect of RH on strain and load is potentially due to the absorption and desorption of water into the chemical structure of the polymer forming the dope film, since the acetyl and nitrile substituent groups of the dope polymers form polar regions where water may be bound. As the water content

of the doped film increases in line with increasing external RH conditions, the inter and intra molecular bonds of the polymer film are disrupted, resulting in re-arrangement and relaxation of the polymer chains, manifested as an increase in strain and decrease in loading.

The reverse occurs when the RH is lowered, at which point water is desorbed enabling closer bonding between polymer chains of the dope, leading to stiffening and contraction of the film which is measured as a decrease in strain and an increase in load. The RH cycling therefore causes reversible chemical changes in the polymer film, at least over the 2 or 3 cycles measured here, which lead to largely reversible physical changes, as is consistent with the repeatable load regain seen in doped and historic samples over several cycles. The reason that samples did not regain 100% of the load as borne at the start of the cycling is likely due to the creep observed during the first hour, which may be an experimental error due to some residual strain being introduced when tightening the clamps.

In the case of un-doped 9F1 Irish Linen the relationship between the load and cycles in RH differed to that of modern doped and historic materials in the immediate period after the RH was altered, when significant jumps in the load were seen. These jumps in the load of undoped fabric may be caused by transverse swelling or contraction of the fibres as RH increases or decreases respectively, causing a corresponding lengthwise shortening or lengthening of the yarns. When RH increases, therefore, the fibre cross section increases and yarns shorten lengthwise increasing the load, and the reverse mechanism occurs when RH decreases and moisture is desorbed causing fibre cross sections to decrease and the yarn length to increase.

These jumps in load are not mirrored in the strain results of the un-doped linen panels, where a corresponding contraction and expansion would be expected in line with the load increase and decrease. This inconsistency between the experiments may be due to experimental error should the expansion and contraction of the strain gauge polymer backing also be responding to changes in moisture and thus mask the signal from the fabric substrate.

Given that the rate and amount of strain measured in both the laboratory and historic materials differed from that of the laboratory control gauge it seems that the gauges are measuring the response of the substrate rather than the results being due to the polymer backing responding, but whether the gauge backing may still undergo some response and so give rise to an error sufficient to mask potentially smaller responses, especially ones over short time scales such as the fibre swelling appears to be, would require further investigation.

Laboratory prepared doped samples and historic materials did not experience the jumps in load measured in the undoped 9F1 linen. If, as proposed above, the jump in load is due to swelling and shrinking of the fibres, this

suggests that the dope treatment prevents, or at least greatly slows, moisture penetration into the fabric itself. The hysteresis effect measured in the strain of fabric panels after doping, which did not occur in un-doped fabrics, is a further sign of a slowed response rate to moisture absorption and desorption when going from an undoped to doped state.

After the initial jump in load of the un-doped yarns, the load behaves in a comparable fashion to the doped and historic samples, in that the load decreases with rising RH and increases when RH drops. Whilst it has been suggested that in doped materials this is due to a relaxation of the doped film, a different mechanism must be responsible in the undoped fabric, which may be explained by the woven structure of the material. In the undoped state, at high RH the woven structure absorbs water which lubricates the weave enabling movement of the yarns at cross over points, and the load thus decreases and strain increases as the weave rearranges.

At low RH, in contrast, the material desorbs moisture making it stiffer and causing an increase in load as the yarns are prevented from re-arranging at the cross over points but once again are fixed in place. The fact that the undoped fabric weave physically alters during this proposed mechanism results in the smaller regains in load and greater creep measured during the tensile frame tests as, once rearranged, the weave cannot return to its previous state.

A change in the physical structure of the un-doped weave may also account for the strain results where an increasing difference in strain between the undoped warp and weft directions was measured after RH cycle 1, with the weft becoming more compressed compared to the warp. This divergence in strain may be attributable to a reorganisation of the un-doped weave structure known as crimp exchange, in which the crimp between the two directions becomes more consistent leading in this case to a compression in the weft as the yarns in this direction divert more from the straight-line path and extension in the warp as they divert less (Figure 9-11).

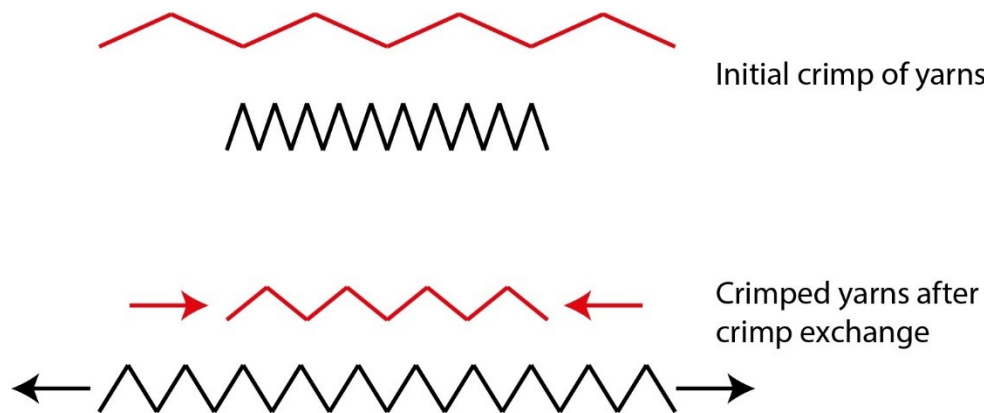


Figure 9-11: Change in yarn length on crimp exchange

The effects of crimp exchange are not apparent in the load experiment, however, where the undoped warp and weft appear to behave very similarly to each other, whereas a greater increase in load might be expected in the weft with cycling compared to the warp if crimp were being exchanged. This difference between the two experiments may be due to the use of uniaxial loading in the tensile frame experiments where only one direction is restrained, compared to the biaxial conditions used in the strain experiments in which both directions are restrained. With only one undoped sample tested in the warp and weft, however, it is not possible to conclude if there are any significant differences or not between the two directions, and further samples would need to be run.

Aside from the divergence of warp and weft on cycling in the un-doped state, there are also differences between the strain and load of the two directions in both the un-doped and doped stages which indicate that the warp is more responsive to fluctuations in RH than the weft. The larger change in strain in the undoped warp compared to undoped weft may be attributable to the larger crimp factor of the warp as the undoped weft, already being relatively straight can undergo little further re-arrangement and lengthening with respect to the warp.

An explanation for the increased size of strain response in the warp direction compared to a reduced response in the weft to RH fluctuations after doping the panels, however, is less clear. The fore-going discussion has suggested that the doping process locks the weave in place eliminating the effect of crimp and that it is then primarily relaxation of the dope film which responds to RH changes, and not the fabric substrate. This would imply that after doping, the warp and weft should respond in a similar manner to RH fluctuations, since it is the doped-film, and not the woven fabric substrate, dominating the material behaviour.

This difference between strain in warp and weft in the doped material is therefore perhaps attributable to the compressive force exerted by the dope film on the warp and weft yarns respectively. In the preceding chapter 8 it was proposed that due to the straighter nature of the weft yarns, a greater component of the compressive force from contraction of the dope film acts in the plane of the panel in this direction than in the warp. The relaxation or stiffening of the dope film, therefore, due to RH fluctuations, does not have an equal effect in the two directions but results in a smaller proportional change in the weft, leading to smaller changes compared to the warp in strain and load.

When the load response of historic samples is compared to the modern materials it appears similar in certain respects to the doped fabrics, with no jumps in load occurring as in un-doped samples and generally

experiencing consistent regains in load after the first change in RH, suggesting that re-arrangements of the fabric weave structures are not occurring, or are very limited. Based on this, changes in load due to cycling of the RH could be attributable to the response of dope films identified in Chapter 7 as being present in nearly all the historic doped-fabric aircraft studied.

It is worth remembering, however, that the historic samples are in many ways very different and much more complex structures than the modern materials tested here. Many of the historic samples are multi-layered constructions, combining a fabric and then potentially several types of dope and paint layers. The response of such complex, multi-layered structures has been shown in the painting's conservation literature to often be the result of interaction between these various components, and insufficient information is available here to deconvolute the contribution of individual layers and their effects.

The presence of so many different components, moreover, may make certain samples more responsive to other variables besides RH not tested here, such as due to thermal expansion and contraction of paint layers. The samples taken from the Vickers Vimy and Antoinette on display in *Flight*, and the Cody Bi-plane from the technical files, experienced the greatest proportional changes in load in response to changes in RH, and it may be no coincidence that these materials also had paint layers, though the response of other painted samples, such as from the Supermarine S6B were not so extreme.

The strain measurements of the aircraft in-situ on *Flight* have demonstrated that the aircraft are responsive to changes in RH in a similar manner to those of lab prepared samples, with an increase in RH leading to an increase in strain and vice versa. This response, moreover, appears to occur immediately with little or no lag time and the rate of response in the historic materials is in most cases roughly 2 times that of the control gauge falling somewhere between the response rates of the warp and weft of the modern lab panels. The only exception to this was the painted surface of the Vickers Vimy port wing which was the only material to have a slower response to changes in RH relative to the control gauge.

When considering conservation approaches, and the properties one would want in a patch for use on a doped-fabric aircraft, it would seem ideal to have a material that responded to RH in an identical manner as the substrate it was bonded to. This would prevent over rapid or extensive responses which might cause excessive contractions or expansions, and thus a compressive or tensile force within the patch which might influence the surrounding historic material. Ideally, this material would also respond in an isotropic or anisotropic manner, depending upon the properties of the substrate being treated.

Comparison of the strain measured in the lab prepared panels to that of the historic material, however, indicates significant differences since there is little or no hysteresis in the historic material, unlike the doped panels, and the historic material was also fairly isotropic in comparison to the doped panels. The age of the historic materials, and resultant physical or chemical changes over repeated RH cycling over many years, may explain these observed differences, but the original nature of the material itself, for example if a weave with isotropic characteristics were used, may also contribute to the current behaviour and so further work is needed to identify whether and how aging mechanisms contribute to this difference between historic and modern materials.

Finally, it is also important to consider how not all locations necessarily respond in a similar manner to changes in RH, and that different approaches might need to be considered for different areas. Whilst the Vickers Vimy fuselage area and the JAP Monoplane responded to RH in a comparable fashion, the Port wing exterior responded in a totally different manner, proving much less responsive to RH than any other material tested. This difference in response could occur for a range of reasons, such as the effect of the cross sectioning on the structure of the fuselage or the presence of other structural components in the wing area as noted which appear to be for access (chapter 6.3.2), but it demonstrates that a one size fits all approach in terms of materials used is not appropriate in this context.

The rapid response of the historic doped-fabric aircraft skins may also be of concern to conservators in terms of the long-term effects of RH cycling on the structural stability of the doped-fabric aircraft, and whether this might eventually lead to cyclic fatigue. This is a possible mechanism by which tears beyond the reach of visitors open, though would need greater investigation to establish the actual risk of such failure mechanisms occurring and, if it is a factor, how such fatigue might be influenced by other factors, such as chemical degradation of the material and whether there is a particular RH range or number of cycles over which the fabric doped-fabric is especially vulnerable.

The final stage of the tensile frame experiment, has provided further evidence that there is a significant difference in maximum tensile loading which historic and modern samples can sustain before failure, which was previously demonstrated in chapter 9. In this experiment, moreover, the inclusion of samples taken from gallery indicates that the materials currently on display in *Flight* are comparable to materials from the technical file, and as such the concerns raised in the previous chapter regarding the likely failure of historic material before modern doped-fabric patches is further supported.

9.5. Summary

There is a relationship between strain and Relative Humidity (RH), as well as load and RH for both modern doped and un-doped fabric. An increase in RH causes an expansion of the material and drop in load, while a drop in RH leads to a contraction and increase in load. The response rate and extent to which modern doped-fabric and un-doped fabric respond to fluctuations in RH differ, however, due to structural differences caused by doping. Structural features of the fabric, such as its crimp factor, have also been linked to anisotropic behaviour in the warp and weft directions respectively.

In-situ monitoring of strain and tensile tests of historic samples taken from the Science Museum technical files and aircraft on display in the *Flight* demonstrated that the historic materials also respond to changes in RH. These results indicate that the response of the historic materials can be rapid and that an increase in RH will result in a relaxation of the material. The mechanism and causes of such responses, however, are potentially more complex than those influencing the response of the modern materials tested and may cause significant variation in the response even in different parts of the same object.

Given the differences measured between the response of the modern doped-fabric panels and the historic aircraft, the use of doped-fabric for patching is not recommended. Further testing of other conservation materials, however, would be required to identify suitable substitutes.

10. The Response of Doped-Fabrics to Patching

10.1. Introduction

Chapters 8 and 9 have explored the effect of applying dope to a fabric and its response to RH, and considered how the results of these experiments may be related to the suitability of using doped-fabric patching as a method for conserving doped-fabric aircraft. This has relied upon studies of the historic and modern materials in isolation from each other, comparing the properties of the two materials when separate and from this extrapolating as to the suitability of doped-fabric as a patching material.

This chapter will investigate the effect of patching itself, and will present the results of experiments in which the effect of doped-fabric patching was studied directly in both historic and modern materials. It will discuss the results of two experiments, one undertaken with modern surrogate doped-fabric panels in which a tear was simulated and then patched, and a comparison with the effect of doped-fabric patches used to conserve tears *in-situ* in *Flight* on the Vickers Vimy.

10.2. Experimental

10.2.1. Strain Gauge Panels

Panels of 9F1 Irish Linen were prepared using the Con1 and Con2 configuration as described in 6.1 and steps 1 and 2 of the preparation methodology, in which the cycling in an undoped state, doping, and then RH cycling in the doped state took place.

This chapter will present the result from stages 3 and 4 of the experimental methodology, in which a tear was simulated in the panels, and then patched. Different patch types were used on the different panel configurations, with Con2 types panels treated in a comparable manner to patches as used on gallery, and Con1 panels treated with a variety of experimental patch shapes. All panels were patched using 9F1 Irish Linen and 9701 Randolph Butyrate dope. The panel configurations, tear locations and patch types used for each respective panel have been repeated in Figure 10-1 for reference.

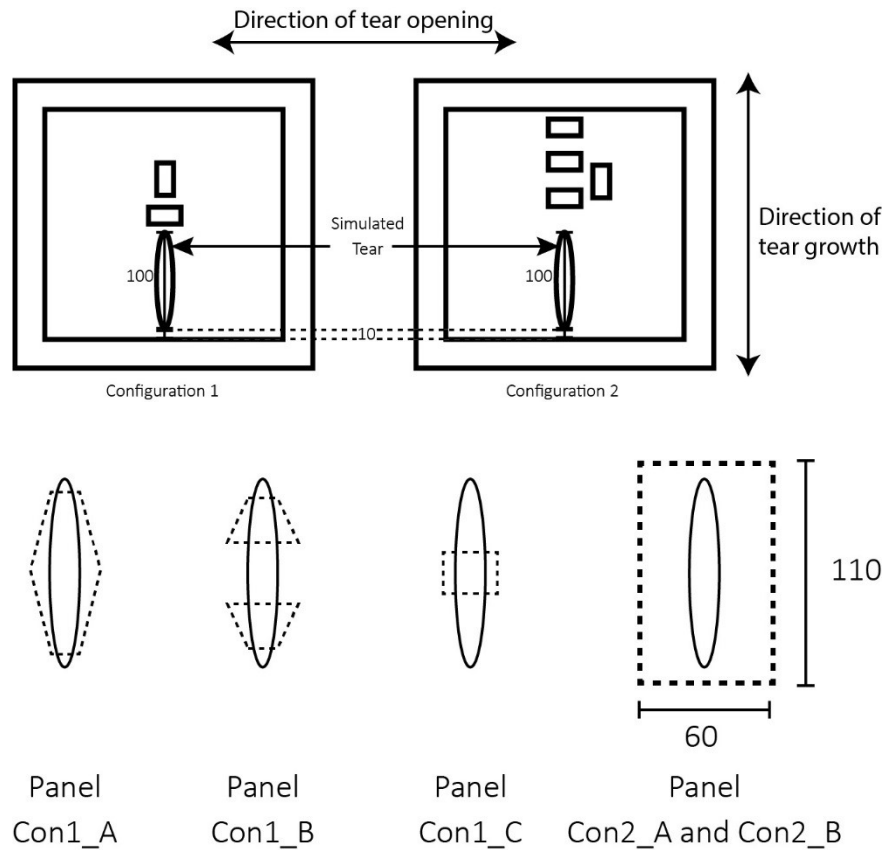


Figure 10-1: Tear orientation and patch types used in laboratory fabric panels

10.2.2. In-Situ Strain Measurements on Gallery

Strain gauges were attached to the doped-fabric skins of historic aircraft on display in the Science Museum's *Flight* as described in 6.2. The results from gauges on the underside of the Vickers Vimy port wing, starboard wing and main fuselage will be presented here as these were in areas of tearing and could subsequently be patched. Patches were applied using the standard museum method as described in 3.3.2, in which a piece of 9F1 Irish Linen is cut to size and given an initial impregnation of 9701 Butyrate dope diluted 50% in acetone. The area of the tear is then lightly sanded, after which the patch was adhered in place using two further coats of dope diluted 50:50 in acetone about 1 hour apart, and then two coats of undiluted dope.

The RH conditions on gallery were not controlled in any further way, and the port and starboard wings were monitored and patched simultaneously, and so were exposed to the same climatic conditions, but the fuselage area was monitored separately due to a limit on the number of gauges that could be monitored at one time. The

monitoring took place during April and May 2017 at which point the museum heating system had been turned off. The location and designation of monitored areas are provided in Table 10-1 and Figure 10-2.

Aircraft	Location	Gauge designation
Vickers Vimy	Lower port wing surface, interior	VV_LPW_Y1 VV_LPW_Y2 VV_LPW_Y3 VV_LPW_Y4
Vickers Vimy	Lower starboard wing, interior	VV_LSW_X1 VV_LSW_Y1 VV_LSW_Y2 VV_LSW_Y3
Vickers Vimy	Main fuselage interior surface	VV_MF_X1 VV_MF_X2 VV_MF_Y1 VV_MF_Y2

Table 10-1: The strain gauges mounted on the Vickers Vimy in areas of tearing

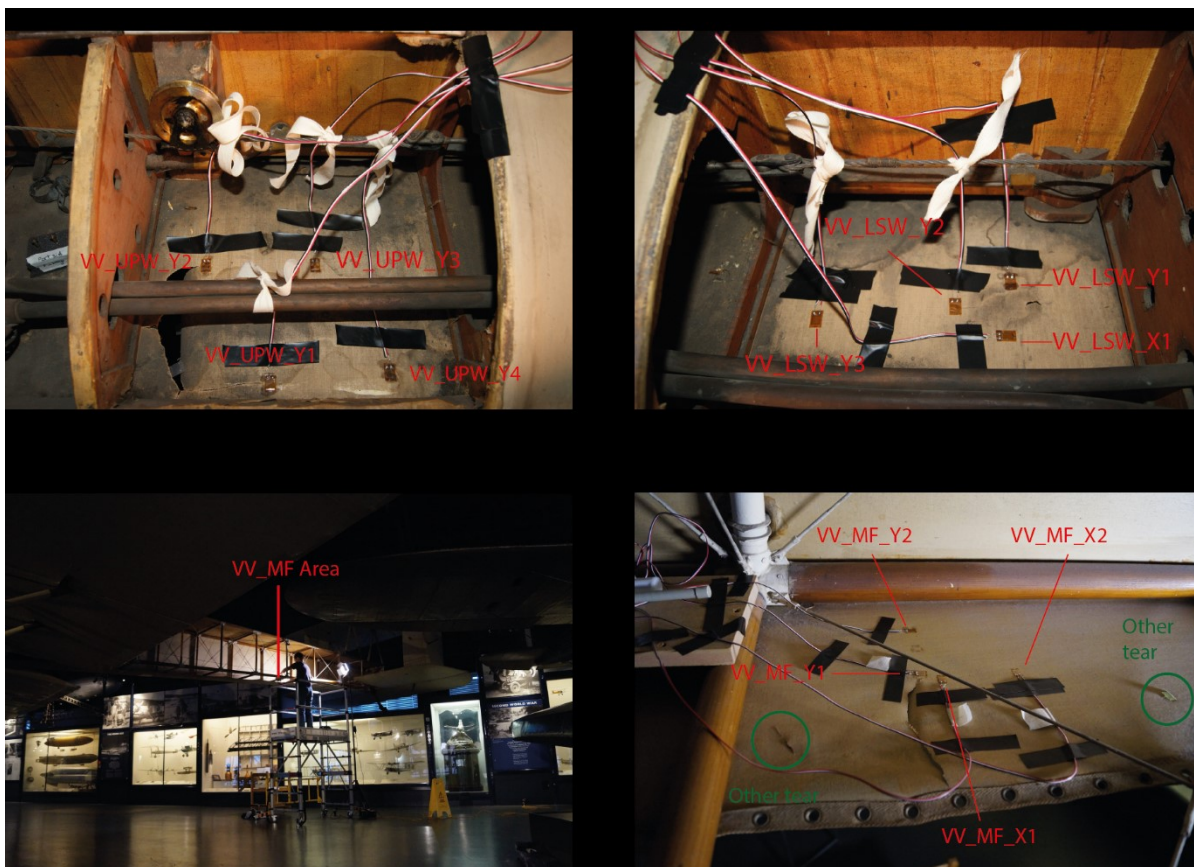


Figure 10-2: The strain gauges around areas of tearing on the Vickers Vimy

10.3. Results

10.3.1. Doped Fabric Panel Results

The strain of panels Con2A and Con2B are shown in Figure 10-3 and Figure 10-4. The panels behave as generally expected based on the results of the previous chapter as increases in RH give rise to an increase in strain and vice versa, and no lag time is recorded. The event of a tear being cut into the panels on day 2 can be observed due to an increase in strain for all gauges. The panels were then exposed to three cycles of RH between days 3-9, at which point they were removed for patching of the simulated tear. After this the panels were returned to the humidity chamber and exposed to two further RH cycles.

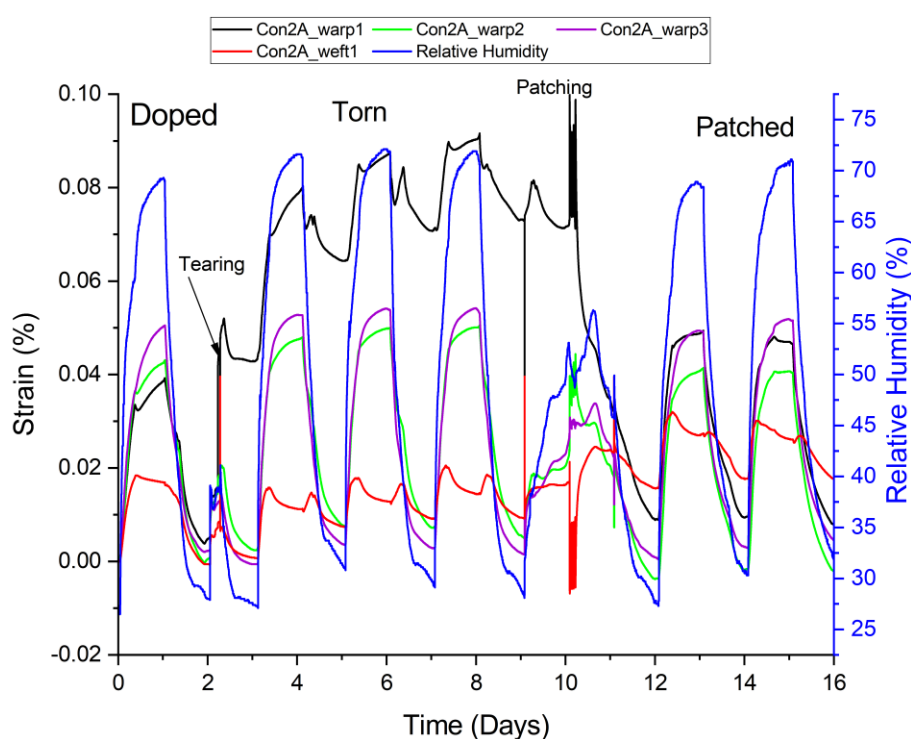


Figure 10-3: The strain of panel Con2A against time. Also shown is Relative Humidity during the same period

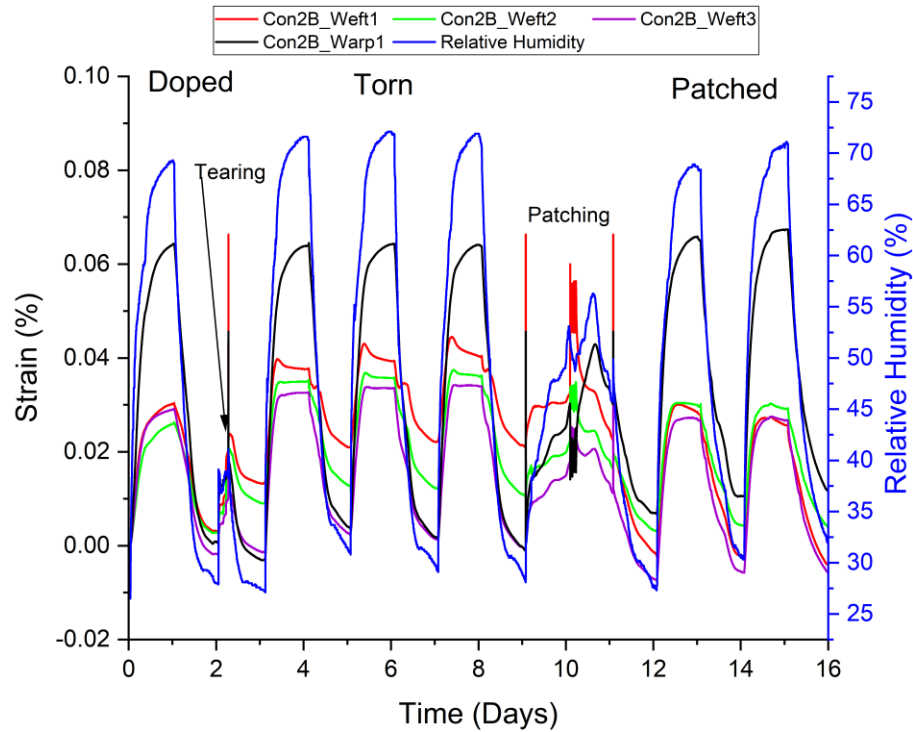


Figure 10-4: The strain of panel Con2B against time. Also shown is Relative Humidity during the same period

The change in strain as a tear was opened in the panels Con2A and Con2B has been plotted in Figure 10-5 and the change in strain after opening against distance from the crack tip is shown in Figure 10-6. In all areas there was an increase in strain as the tear opened, with the largest increases occurring the closer the area was in relation to the crack tip. In panel Con2A where the tear opened across the warp direction, the increase in strain fell away exponentially with distance from the tear tip, with Con2A_Warp1 closest to the panel centre experiencing by far the largest change. In panel Con2B in which the tear opened across the weft direction, however, the change in strain appears to be inversely directly proportional over the distance investigated.

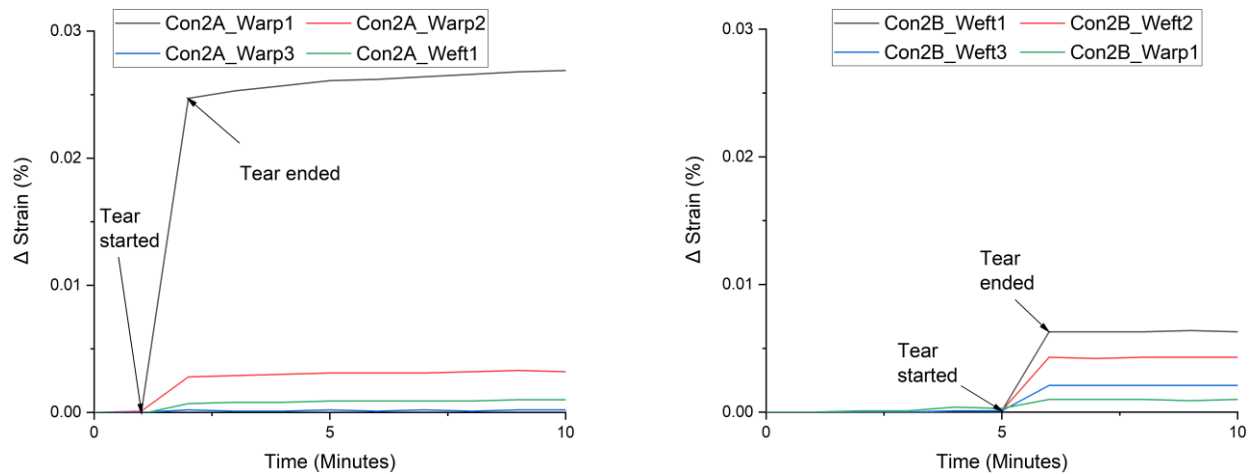
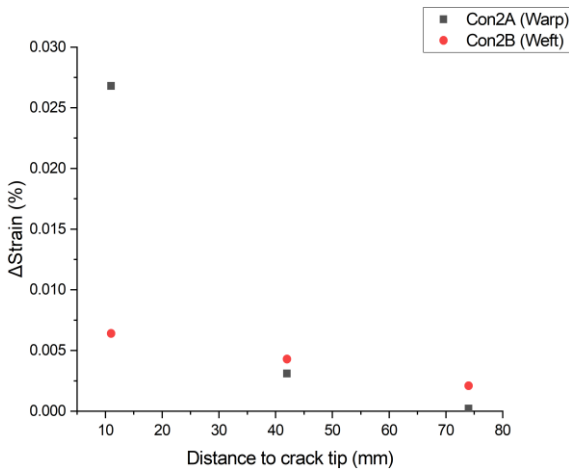


Figure 10-5: The change in strain in panels Con2A and Con2B when a tear was cut in the doped-fabric panel.



Distance to crack tip (mm)	Con2A Warp (%)	Con2B Weft (%)
10	0.0268	0.0064
42.5	0.0031	0.0043
75	0.0002	0.0021

Figure 10-6: Change in strain of panels Con2A and Con2B with distance from the crack tip. On Con2A the tear opened across the warp and in line with the weft, and in Con2B the tear opened across the weft and in line with the warp

The application of the patch to the tear area caused a change in the strain in the locations of the strain gauges. When dope was applied to the patch there was an immediate, rapid increase in strain in direction across the tear (Figure 10-7), after which the strain decreased. The effect of this initial increase in strain and subsequent contraction decreases with distance from the crack tip, and this difference in response over distance appears broadly comparable between the two panels (Table 10-2). The opposite strain response was observed in the gauges normal to the direction of the tear opening on both panels, at Con2A_Weft 1 and Con2B_Warp1. In these instances, the initial application of dope led to a decrease in strain which was then followed by a period of increasing strain.

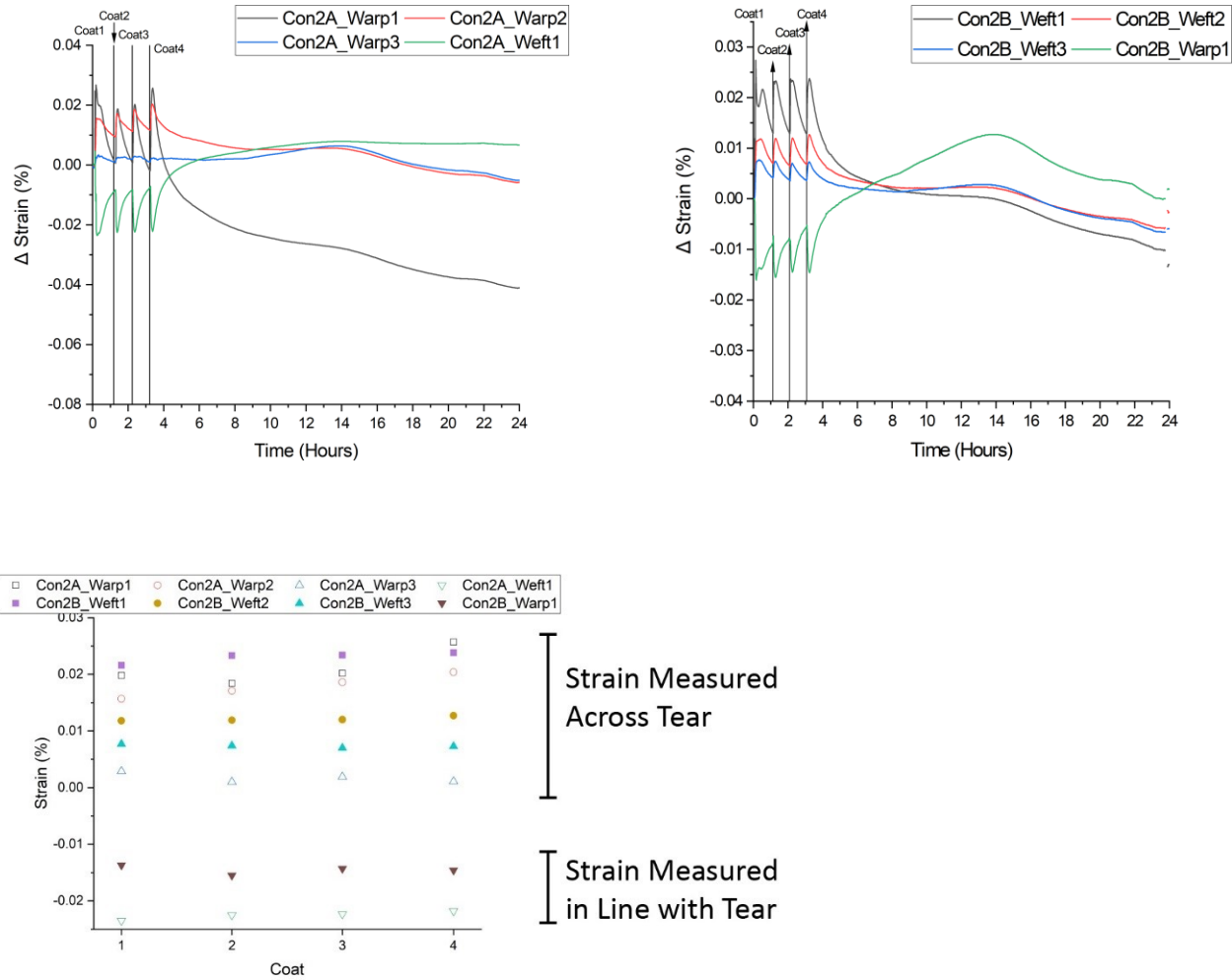


Figure 10-7: Top; the change in strain during the application of patches to panels Con2A (left) and Con2B (right). Bottom; the maxima and minima values of strain at each gauge location during patching. On Con2A the tear opened across the warp and in line with the weft, and in Con2B the tear opened across the weft and in line with the warp

Coat	Con2A_Warp 1 Strain (%)	Con2A_Warp 2 Strain (%)	Con2A_Warp 3 Strain (%)	Con2A_Weft 1 Strain (%)	Con2B_Weft 1 Strain (%)	Con2B_Weft 2 Strain (%)	Con2B_Weft 3 Strain (%)	Con2B_Warp 1 Strain (%)
1	0.0198	0.0157	0.0029	-0.0235	0.0216	0.0118	0.0077	-0.0137
2	0.0184	0.0171	0.001	-0.0225	0.0233	0.0119	0.0074	-0.0155
3	0.0202	0.0186	0.0019	-0.0223	0.0234	0.012	0.007	-0.0143
4	0.0257	0.0204	0.0011	-0.0218	0.0238	0.0127	0.0073	-0.0146

Table 10-2: Maxima and minima values of strain measured during patching with each coat of dope applied

Once torn, the relationship between RH and strain at the crack tip is altered. Figure 10-8 and Figure 10-9 compare the strain response of the different areas monitored on panels Con2A and Con2B to changes in RH in the undamaged doped state, after a tear was opened and after patching. For the un-damaged doped-fabric panels an increase in RH can be seen to cause an increase in strain and an RH decrease the reverse, with strain returning to a similar level after each cycle and, as expected from chapter 9, the warp direction has a greater strain response than the weft.

After tearing, however, the strain response of the panels to RH changed particularly in the areas closest to the tear tip, leading to an overall increase in strain at the tear tip over the 3 cycles. An increase in RH caused the strain to increase, but a decrease in RH did not then result in a comparable contraction. The size of this effect reduces with repeated cycles, and the greatest opening occurred with the first cycle. The gauges located furthest from the tip appeared to be relatively unaffected compared to the gauge located at the tip.

Upon patching, the strain was reduced to a level comparable to that before the tear was introduced at all the locations monitored. In some places the decrease in strain was large enough that the overall strain was reduced slightly compared to the starting strain in the undamaged doped. There also appeared to be a reduction in the hysteresis effect and the response shifts slightly to the right indicating a lower strain is occurring at the same RH level than previously.

At the gauges located in line to the opening of the crack, however, the strain response after patching was the opposite to that of the gauges monitoring strain across the crack tip opening. In both Con2A_Weft 1 and Con2B_Warp1, there is a slight increase in strain of approximately 0.01% compared to the strain recorded at the end of torn RH cycling stage.

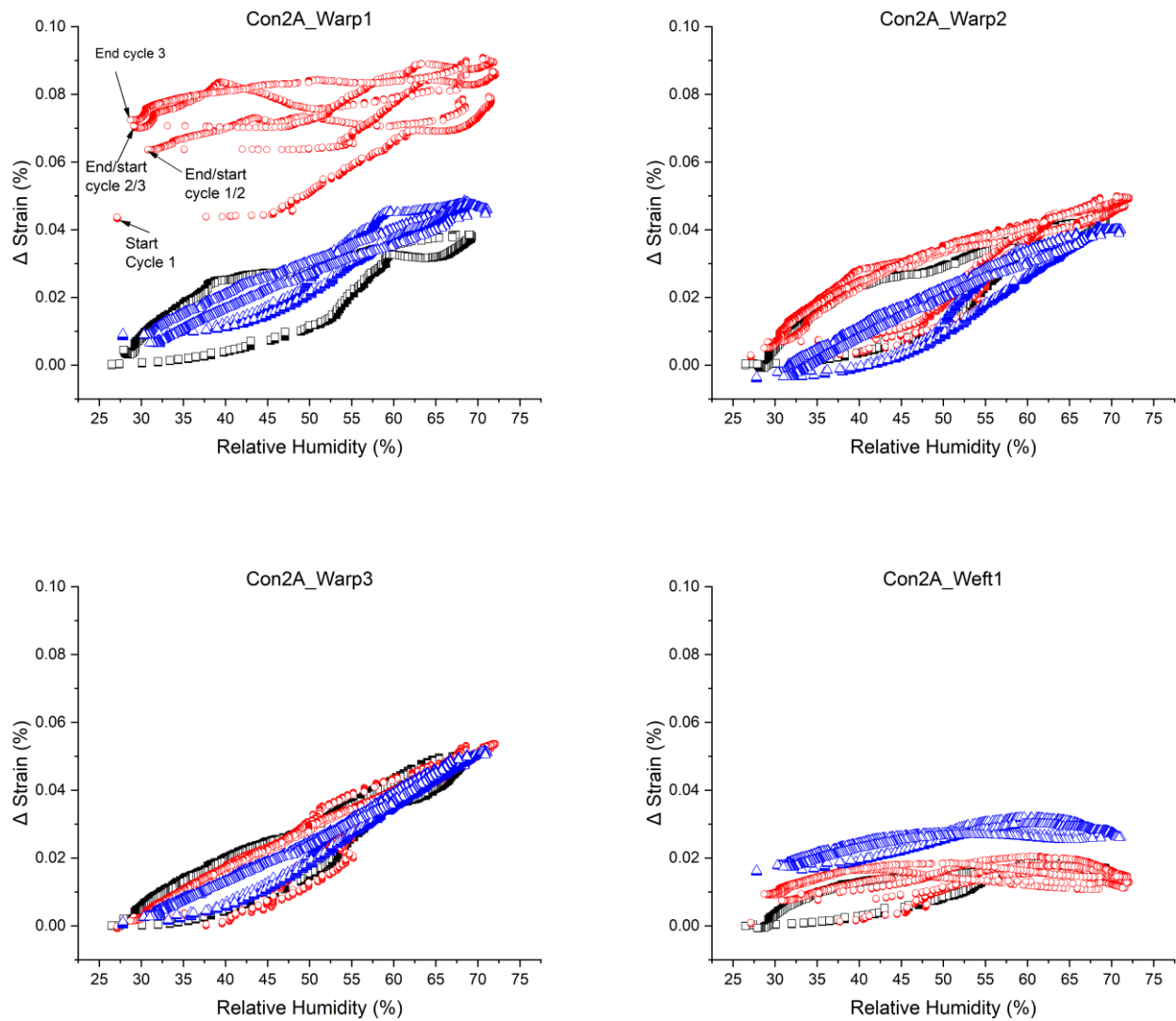


Figure 10-8: Change in strain of Con2A panel against Relative humidity at the different locations monitored. The tear opened across the warp and in line with the weft

□ = Doped panel before tearing,
 O = Doped panel after tearing,
 Δ = Doped panel after patching

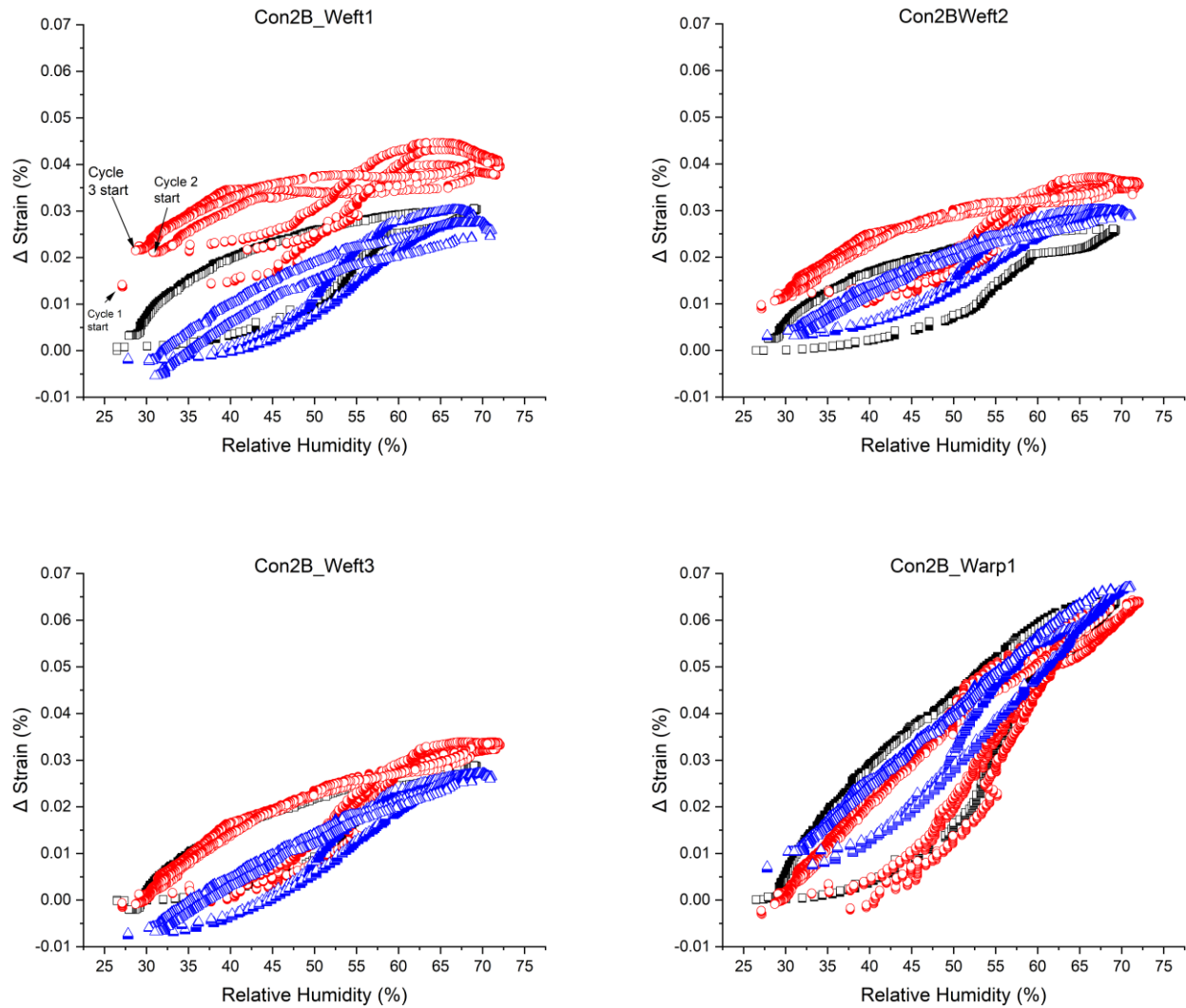


Figure 10-9: Change in strain of Con2B panel against Relative Humidity at the different locations monitored. The tear opened across the weft and in line with the warp

□ = Doped panel before tearing,
 O = Doped panel after tearing,
 Δ = Doped panel after patching

The change in strain of the panels over the course of the experiment can be seen in Figure 10-10, where the average strain at $30 \pm 0.5\%$ RH has been plotted against time and the figures are provided in Table 10-3 and Table 10-4. The increasing strain on tearing and RH cycling are observable, and the subsequent contraction after patching across the tear, whilst there is a slight increase in strain in the direction in line with the tear opening.

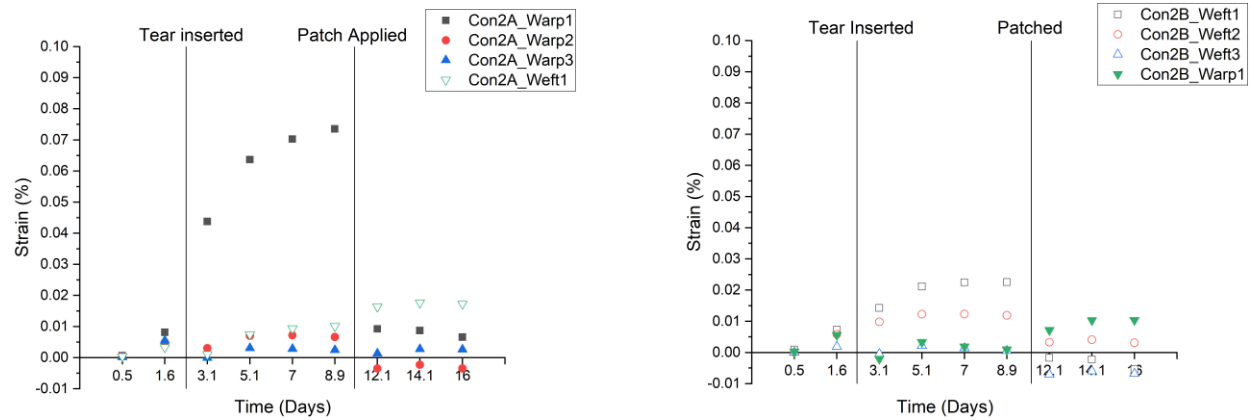


Figure 10-10: The strain measured on panels Con2A (left) and Con2B (right) at $30\pm0.5\%$ RH over the course of the experiment

Time	Con2A_Warp1	Con2A_Warp2	Con2A_Warp3	Con2A_Weft1
(Days)	(%)	(%)	(%)	(%)
0.5	0.0006	0.0005	0.0002	0.0004
1.6	0.0082	0.0050	0.0055	0.0033
3.1	0.0438	0.0031	-0.0001	0.0011
5.1	0.0637	0.0070	0.0031	0.0075
7	0.0703	0.0072	0.0028	0.0094
8.9	0.0736	0.0067	0.0024	0.0101
12.1	0.0093	-0.0035	0.0013	0.0164
14.1	0.0087	-0.0023	0.0028	0.0177
16	0.0066	-0.0034	0.0026	0.0173

Table 10-3: Average Strain of panel Con2A at $30\pm0.5\%$ RH over the course of the experiment

Time	Con2B_Weft1	Con2B_Weft2	Con2B_Weft3	Con2B_Warp1
(Days)	(%)	(%)	(%)	(%)
0.5	0.0009	0.0001	0.0000	0.0002
1.6	0.0073	0.0059	0.0019	0.0056
3.1	0.0143	0.0098	-0.0004	-0.0021
5.1	0.0212	0.0123	0.0021	0.0033
7	0.0225	0.0123	0.0014	0.0019
8.9	0.0226	0.0119	0.0005	0.0009
12.1	-0.0017	0.0033	-0.0071	0.0072
14.1	-0.0023	0.0041	-0.0060	0.0103
16	-0.0054	0.0031	-0.0068	0.0104

Table 10-4: Average Strain of panel Con2B at $30\pm0.5\%$ RH over the course of the experiment

The cycling process of Con1 type panels are shown in Figure 10-11. This figure shows the point at which tears were cut into the panels and when patches were inserted, and the periods over which the panels underwent RH cycling in a doped, then torn and finally patched condition. The response of the graphs to fluctuating RH as in previous experiments are seen and the increase in strain due to the introduction of a tear is marked.

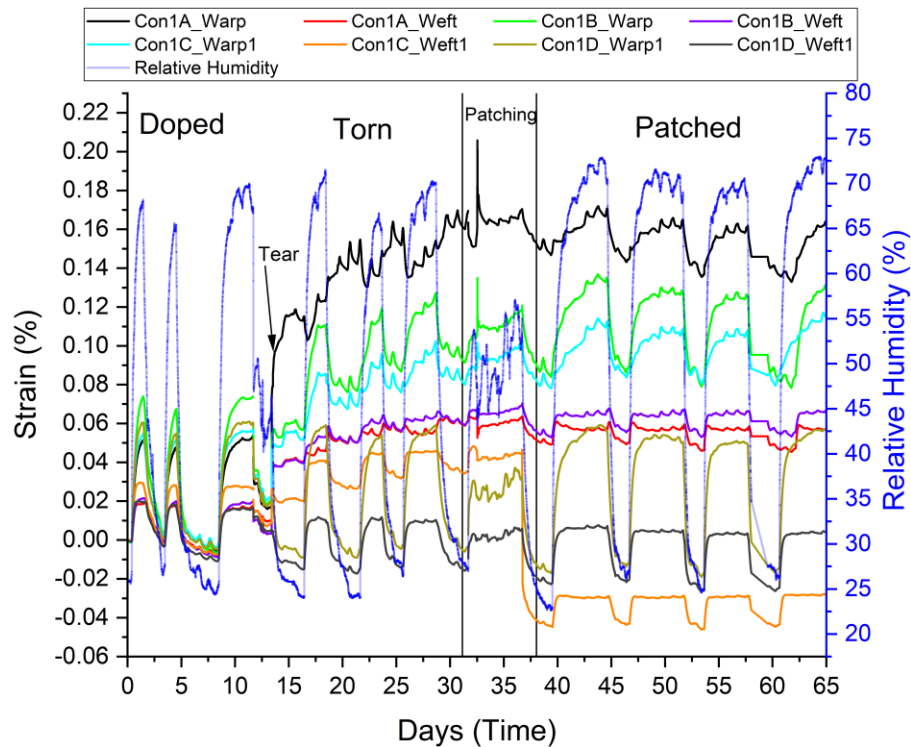


Figure 10-11: The strain in type Con1 doped-fabric panels against time.

Making a tear in Con1 type panels resulted in an increase in strain measured in the direction across the tear (the warp) and normal to this (weft), and subsequent cycling of the RH caused an increase in strain as was observed in Con2 type panels (Figure 10-12 and Figure 10-13). The use of the smaller patches, however, resulted in a different response to that noted in the previous experiment as the strain across the tear opening did not return to a level comparable to that before the tear was introduced. There also did not appear to be an increase in the strain in the direction normal to the tear opening as in the patched Con2 panels.

The patch type used on Con1A appeared to have the largest influence on strain, reducing it by 0.0192% between days 30 and 52. Con2B was second most effective reducing strain by 0.0052%, followed by Con1C where the strain measured increased by 0.0026%. It should be noted in the case of Con1C, however, that some creep of

the fabric panel appears to have occurred in the weft direction after the patch was applied, as a large sudden drop in strain occurs in the weft direction around day 37, which may have affected the amount of contraction measured.

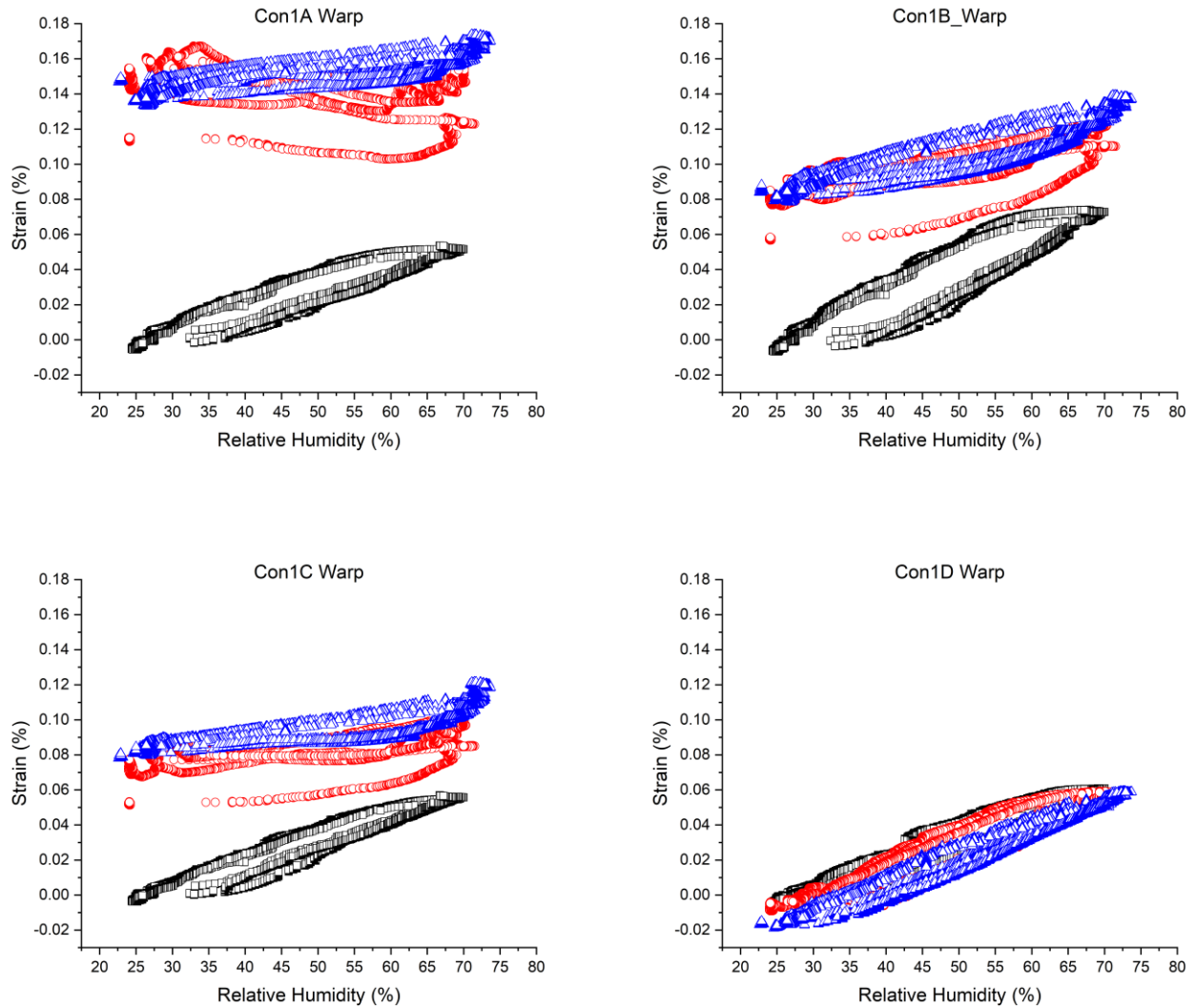


Figure 10-12: Change in strain of Con1 panels in the warp direction (across the tear) against Relative Humidity.

- = Doped panel before tearing,
- = Doped panel after tearing,
- △ = Doped panel after patching

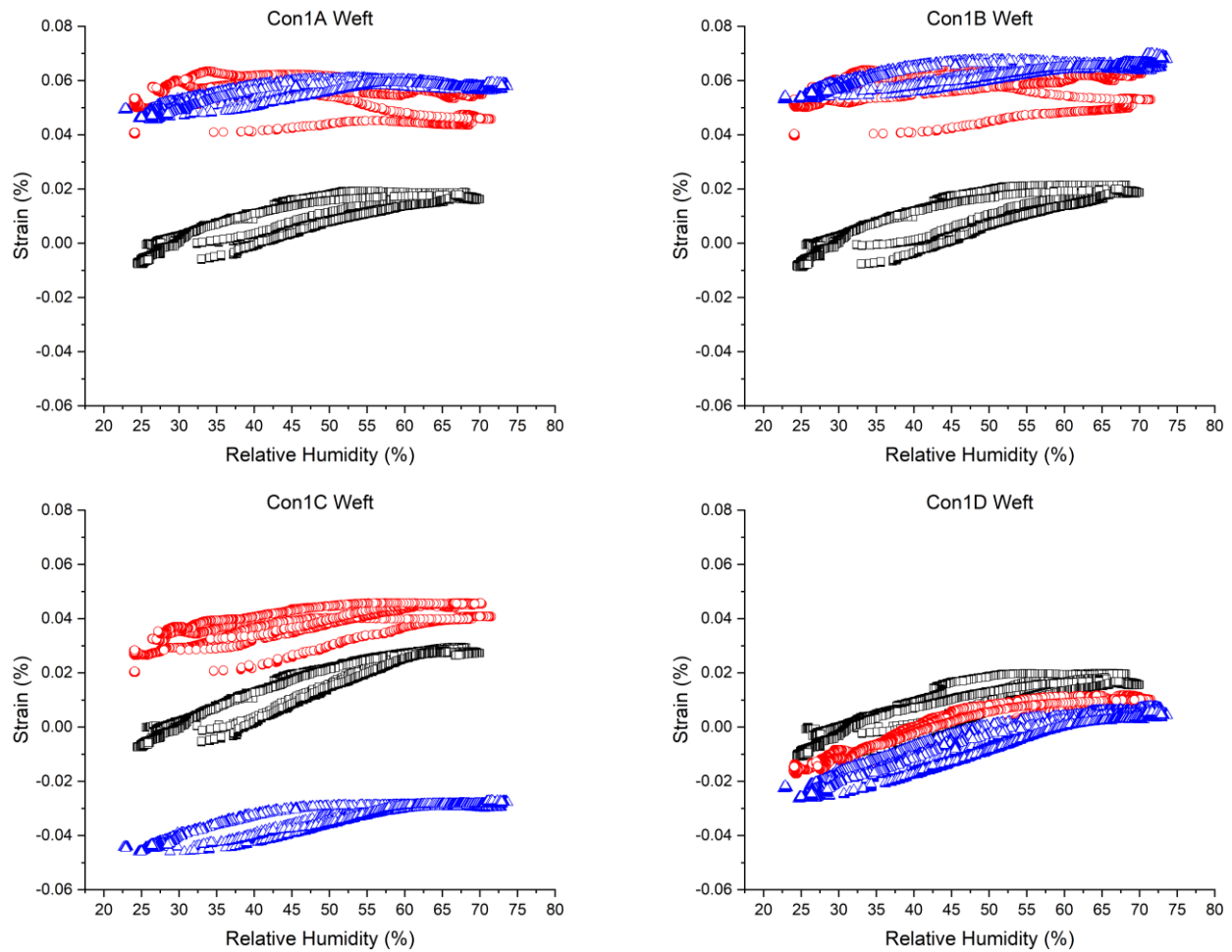


Figure 10-13: Change in strain of Con1 panels in the weft direction (in line with the tear) against Relative Humidity.

□ = Doped panel before tearing,
 ○ = Doped panel after tearing,
 Δ = Doped panel after patching

The change in strain of the panels over the course of the experiment can be seen in Figure 10-14, where the average strain at $30 \pm 0.5\%$ RH has been plotted against time and the figures are provided in Table 10-5. The increasing strain on tearing and RH cycling are observable, and the subsequent contraction of the panel Con1A whilst Con1B and Con1C remained comparatively stable. No increases in strain occurred in any of the weft-oriented strain gauges located in line with the tear opening.

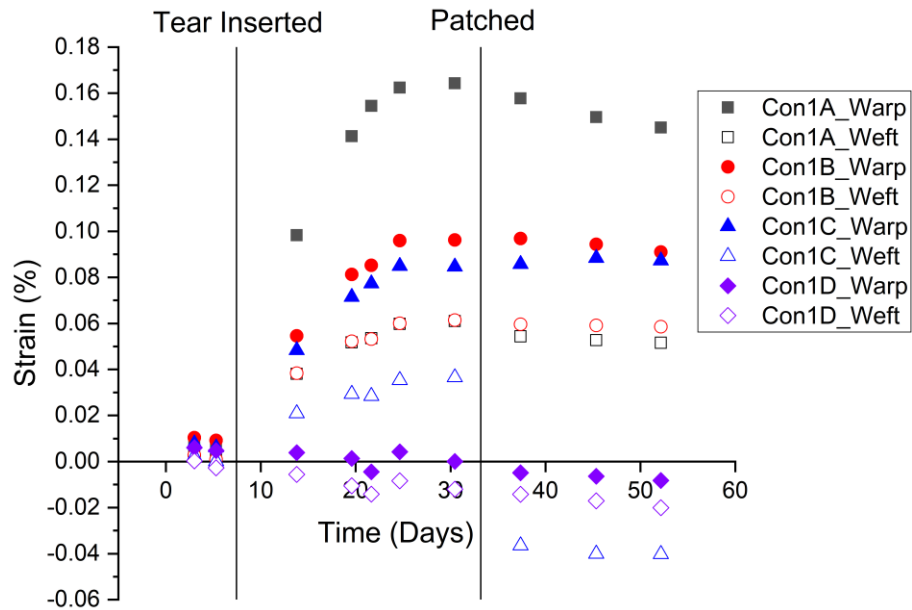


Figure 10-14: The strain measured in the warp and weft on Con1 panels at 30±0.5% RH over the course of the experiment

Time (Days)	Con2A_ Warp (%)	Con1A_ Weft (%)	Con1B_ Warp (%)	Con1B_ Weft (%)	Con1C_ Warp (%)	Con1C_ Weft (%)	Con1D_ Warp (%)	Con1D_ Weft (%)
3.0	0.0085	0.0029	0.0104	0.0028	0.0078	0.0022	0.0060	0.0002
5.3	0.0073	0.0011	0.0091	0.0009	0.0061	0.0000	0.0047	-0.0027
13.8	0.0983	0.0381	0.0546	0.0384	0.0483	0.0209	0.0038	-0.0056
19.6	0.1413	0.0517	0.0812	0.0522	0.0714	0.0294	0.0013	-0.0105
21.7	0.1545	0.0535	0.0852	0.0532	0.0773	0.0284	-0.0045	-0.0141
24.6	0.1624	0.0597	0.0960	0.0600	0.0849	0.0353	0.0042	-0.0084
30.5	0.1642	0.0610	0.0962	0.0614	0.0846	0.0365	0.0000	-0.0119
37.4	0.1577	0.0543	0.0969	0.0596	0.0857	-0.0365	-0.0049	-0.0142
45.4	0.1496	0.0527	0.0943	0.0591	0.0884	-0.0401	-0.0064	-0.0171
52.2	0.1450	0.0515	0.0910	0.0585	0.0873	-0.0402	-0.0082	-0.0201

Table 10-5: Strain of Con1 panels at 30±0.5% RH over the course of the experiment

Of further note was an apparent increase in response to temperature after tearing. An increase in temperature corresponds to an increase in strain, and a decrease in temperature a decrease in strain. The effect is most pronounced in panels in which a tear was cut, though Con1A appears to be particularly effected. Con1D in which

no tear was cut shows some small response to temperature, though this appears much more limited compared to the torn panels.

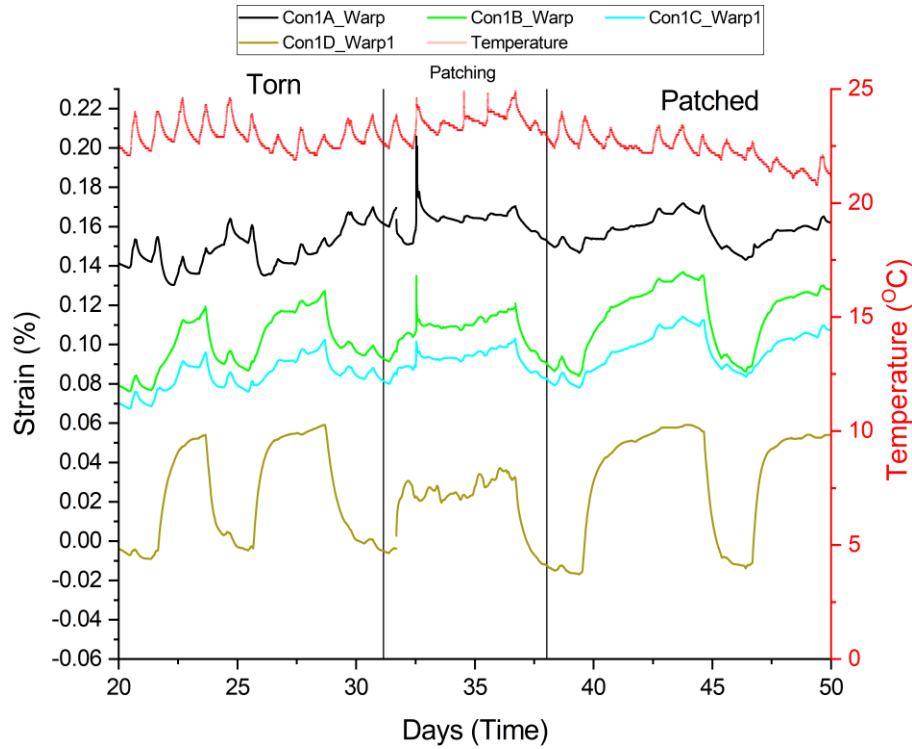


Figure 10-15: Strain of Con1 panels in the warp direction and temperature against time in the period between having being torn and then having been patched. The torn panels appear to have a greater strain response to temperature, compared to panel Con1D which was left untorn

Also of note was the continued behaviour of panel Con1D which was left untorn to act as a control. Over the entire period of the experiment the strain of the panel decreased overall in both warp and weft directions by about 0.02% and 0.01% respectively over the 60 days of testing (Figure 10-16). This decrease in strain occurred at all RH levels, though did appear to be levelling off more at higher RH levels.

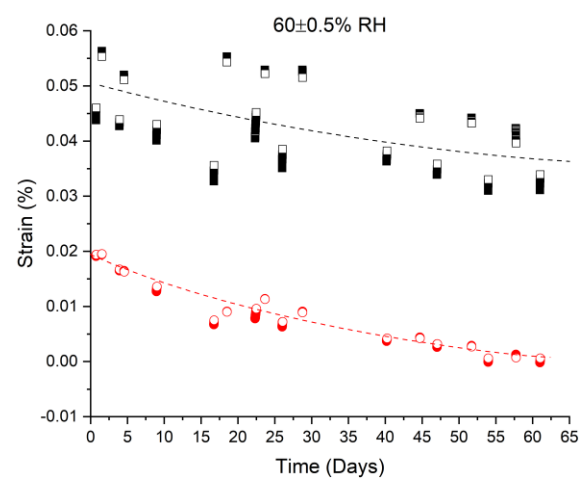
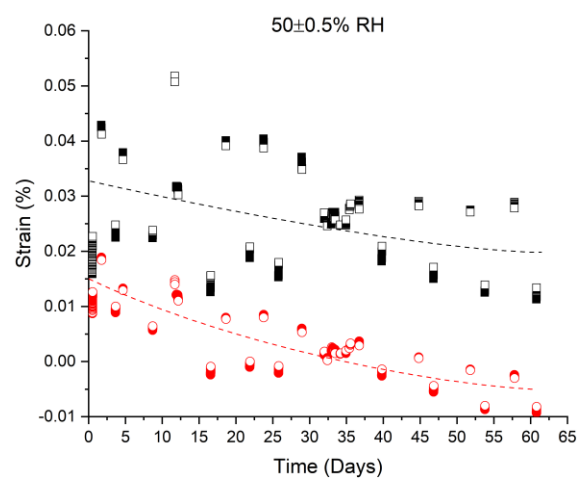
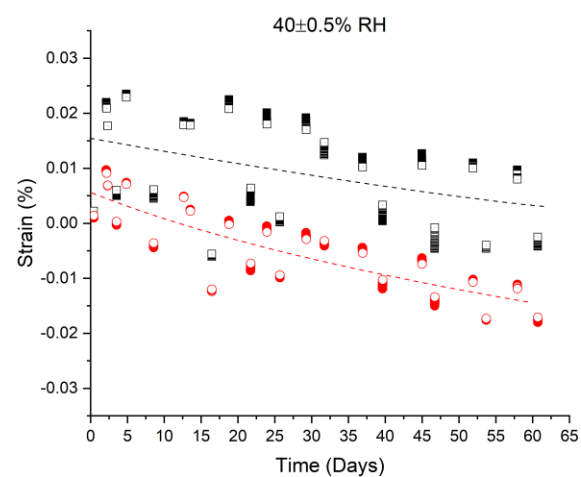
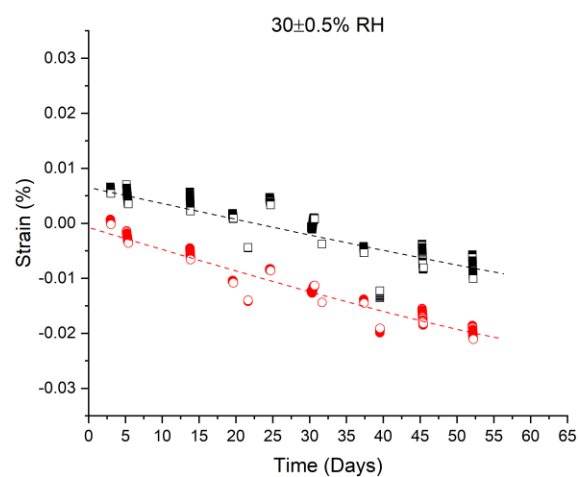
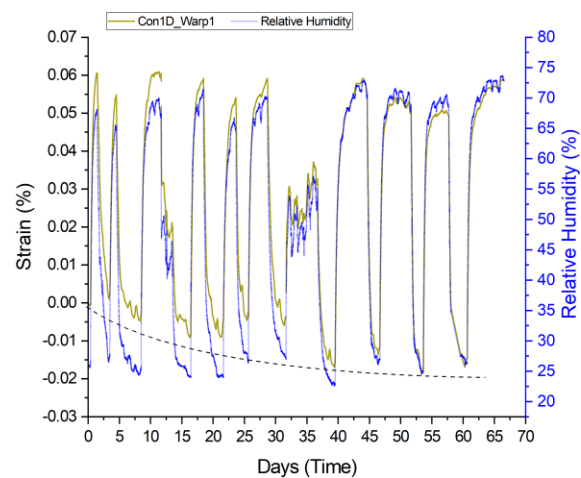
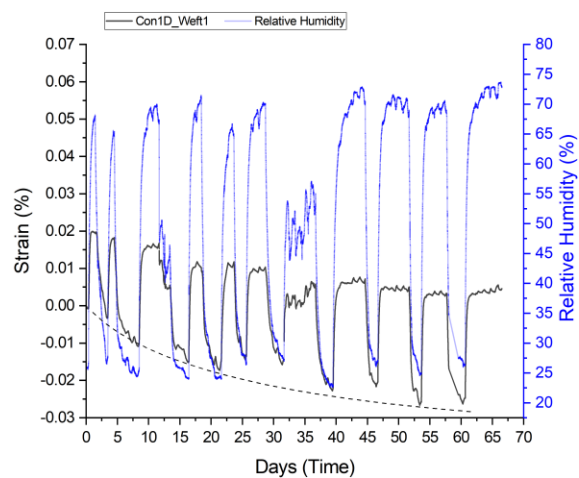


Figure 10-16: Strain of Panel 1D which was left untorn. Top strain in the warp and weft, and RH against time. Middle and bottom the strain at different RH boundaries against time. N.B different scale ranges have been used between the top middle and bottom rows.

10.3.2. In-Situ Monitoring of Historic Aircraft on Display

The areas monitored on *Flight* using strain gauges had a similar response to RH as found in previous experiments as a rise in RH led to an increase in strain, and a drop in RH a decrease in strain (Figure 10-17). Some delay was measured between a change in RH and the response of the doped-fabric in the port and starboard wing areas of up to approximately one hour before patching and this difference in response appeared to increase after the patch had been applied, rising to approximately 3 hours once patched (Figure 10-18).

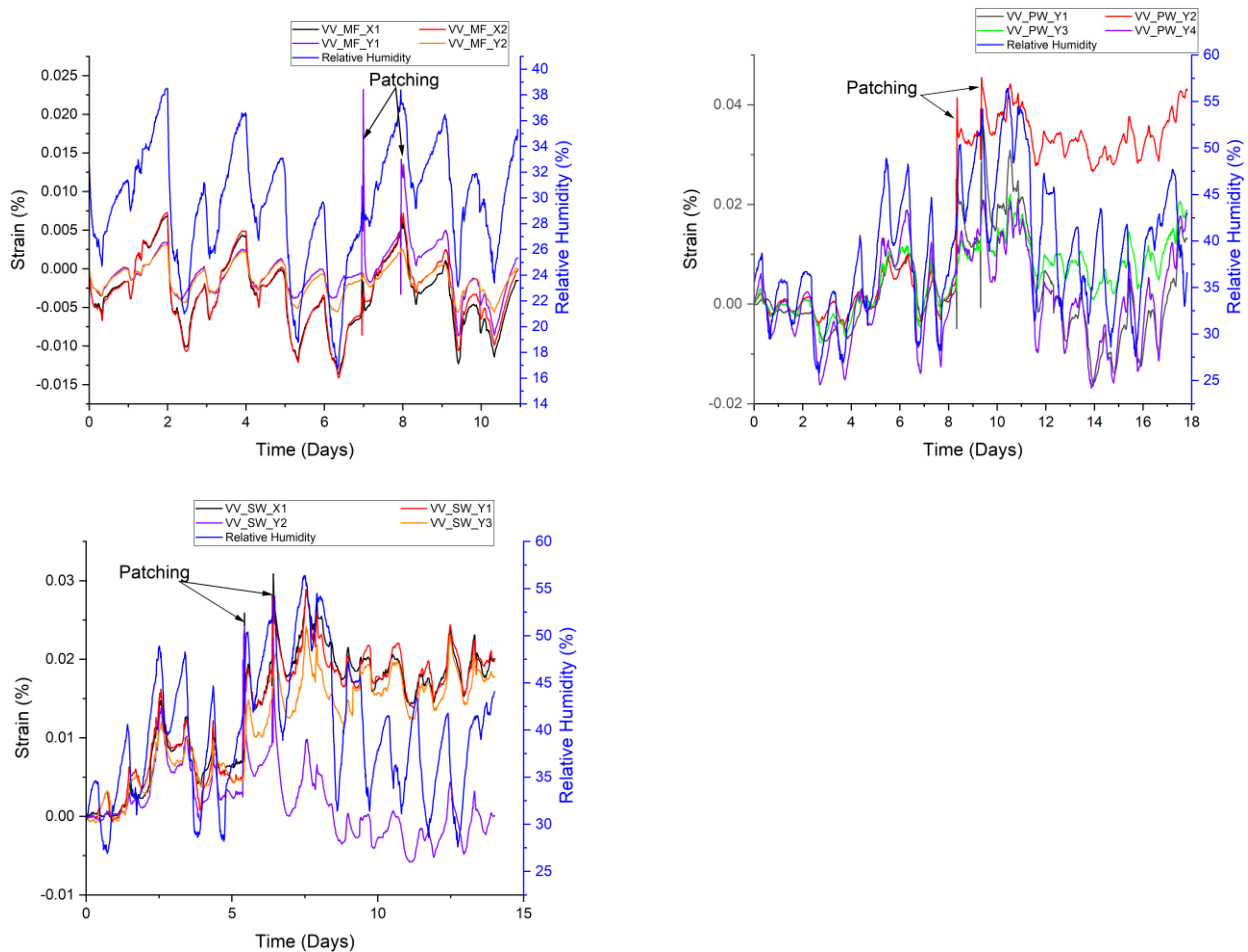


Figure 10-17: Strain measurements of the Vickers Vimy tear areas and the Relative Humidity against time

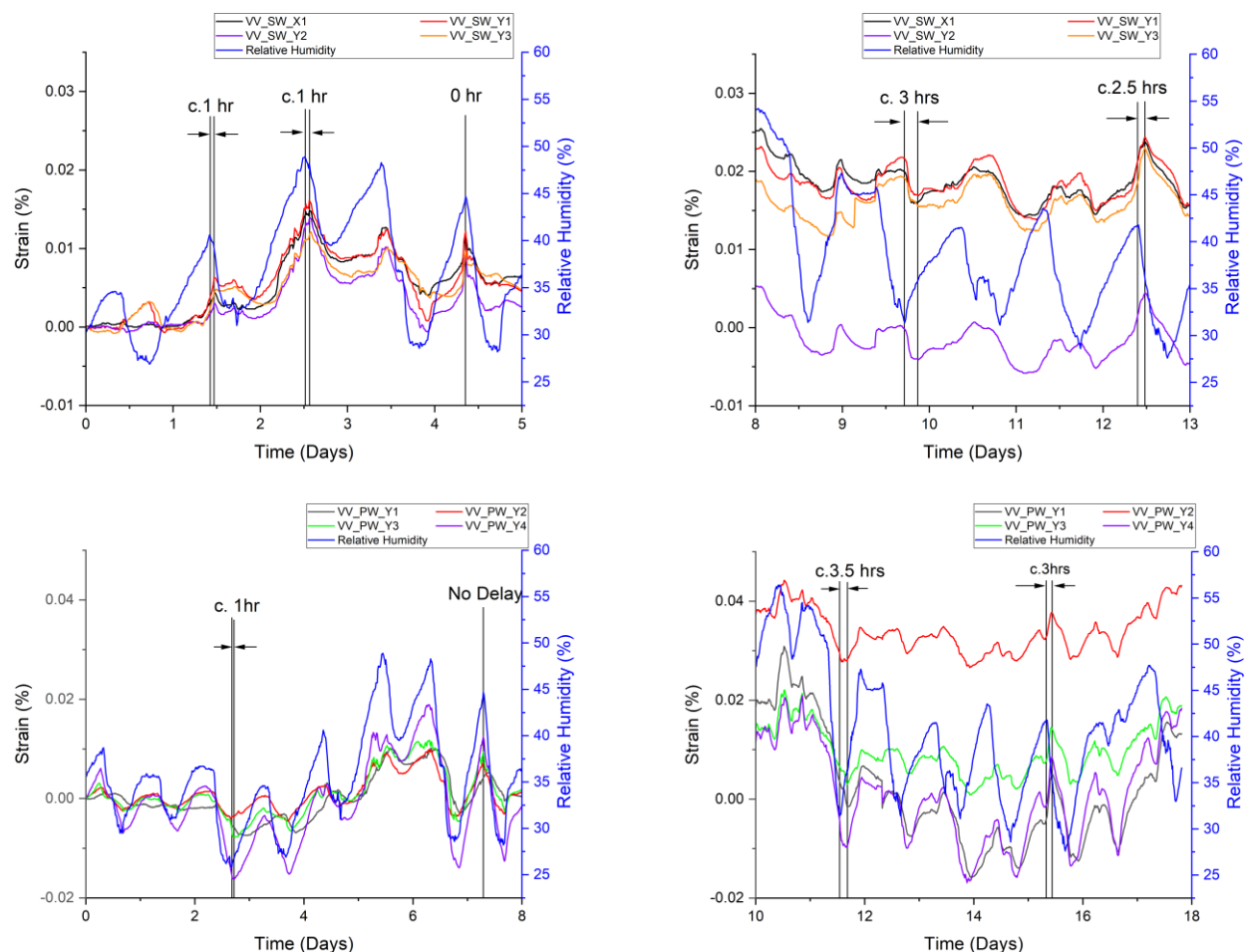


Figure 10-18: The strain of the Vickers Vimy port and starboard wing tear area against relative humidity before patching (left) and after patching (right) with the time delay between a change in RH and change in strain marked

When patches were applied, the strain of the aircraft skin responded in a comparable manner to previous experiments in which dope was applied to fabric substrates. The initial response of the fabric was a rapid increase in strain, which was then followed by a slower, more prolonged contraction, before the influence of RH on strain response became dominant (Figure 10-19).

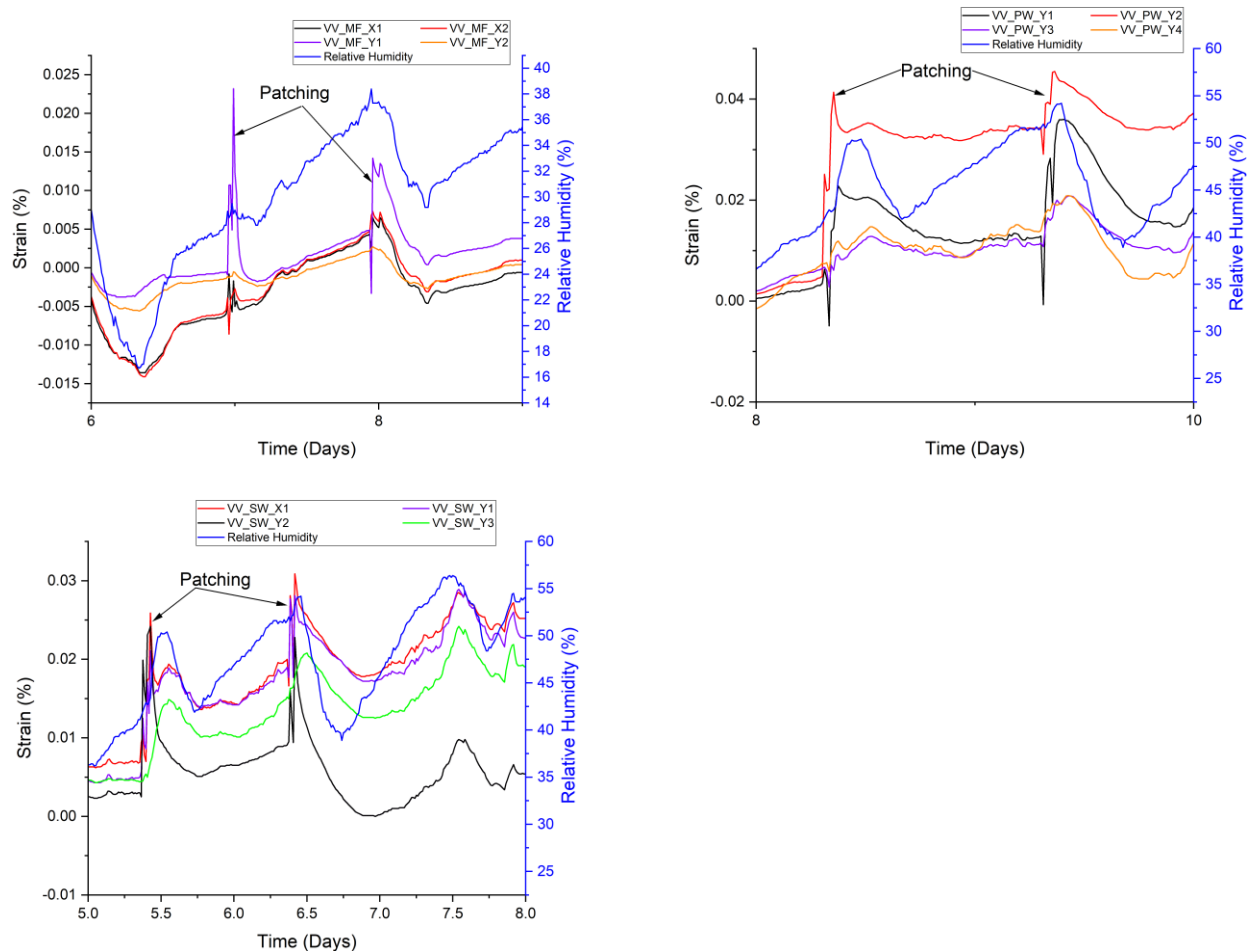


Figure 10-19: Strain measurements of the Vickers Vimy tear areas and the Relative Humidity against time during patching

The response of certain locations in the aircraft skin to changes in RH altered after the application of a patch. For the Vickers Vimy Fuselage area, the strain measured in the X direction, the width of the fuselage, remained fairly consistent before and after patching but changes occurred in the Y direction, lengthwise along the fuselage. The response of the location monitored nearest the tear increased nearly 3 times in the Y direction, whilst that of the location 10 cm away increased 1.5 times (Figure 10-20 and Table 10-6).

The application of the patch also appears to have resulted in an overall decrease in strain. Gauge MF_X1 underwent the largest consistent decrease in strain of approximately -0.04%. Gauges MF_X2 and MF_Y2, further away from the crack tip, contracted between approximately -0.001 and -0.003%. The overall contraction of MF_Y1 was not consistent across all RH values, being greatest at 30%, but experiencing an overall expansion at 35%, reflecting the change in response of the fabric at this location.

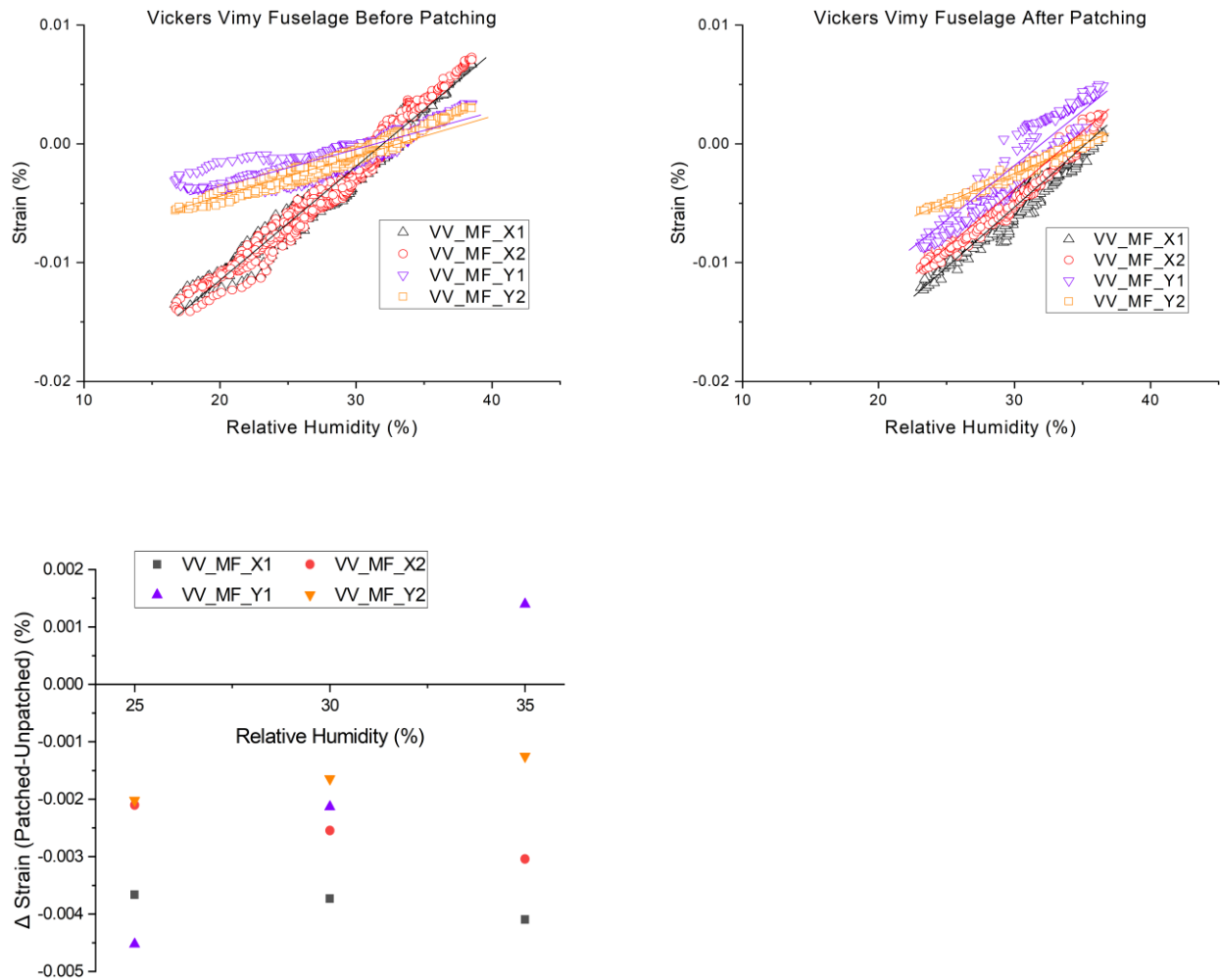


Figure 10-20 Top, strain measurements of the Vickers Vimy Fuselage tear area against Relative Humidity, comparing the response before and after patching. Bottom, the average change in strain measured against relative humidity after patching.

The response of the Port wing area to changes in RH is far less consistent than that of the fuselage area, and there is not as strong a correlation between the RH and strain (Figure 10-21). The response of the fabric also appears to alter after application of patches, though in an inconsistent manner, and the correlation between RH and strain becomes weaker. The overall strain of most gauges, however, remains reasonably consistent, with only PW_Y2 changing markedly by approximately 0.03%. In terms of response to RH, the rates remained fairly consistent for most of the locations, barring PW_Y1 where the rate increased by 1.6 times.

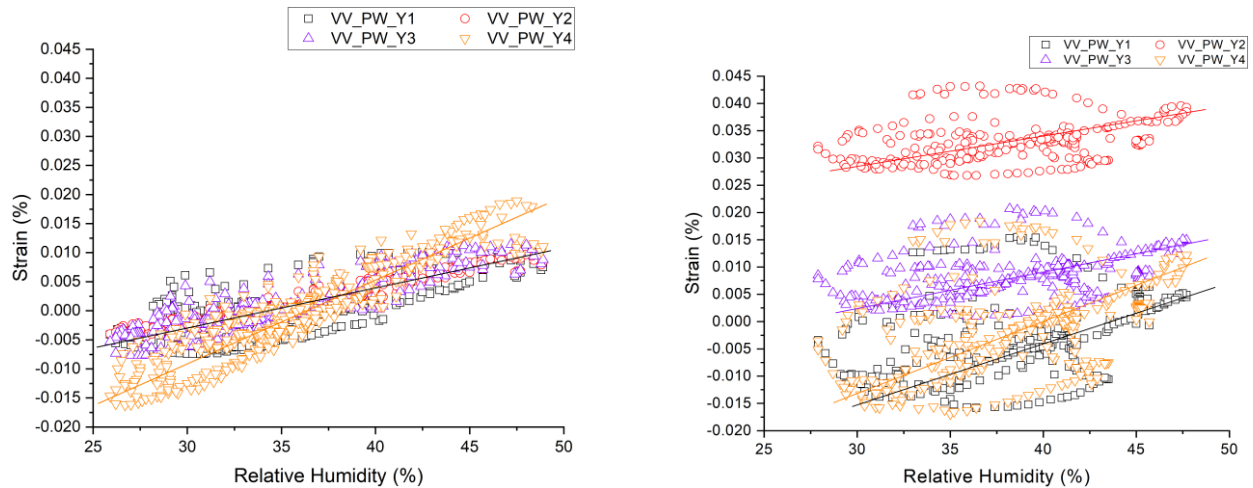


Figure 10-21: Strain measurements of the Vickers Vimy port wing tear area before (left) and after (right) patching against Relative Humidity

In the starboard wing, the expected correlation between RH and strain disappeared after patching, with no apparent overall change in strain with a change in RH. This change occurred in all locations monitored both close to and at a distance from the tear location. The overall change in strain of the gauges before and after patching also varied, with SW_Y1, SW_Y3 and SW_X1 at 0.02% more strain than SW_Y2.

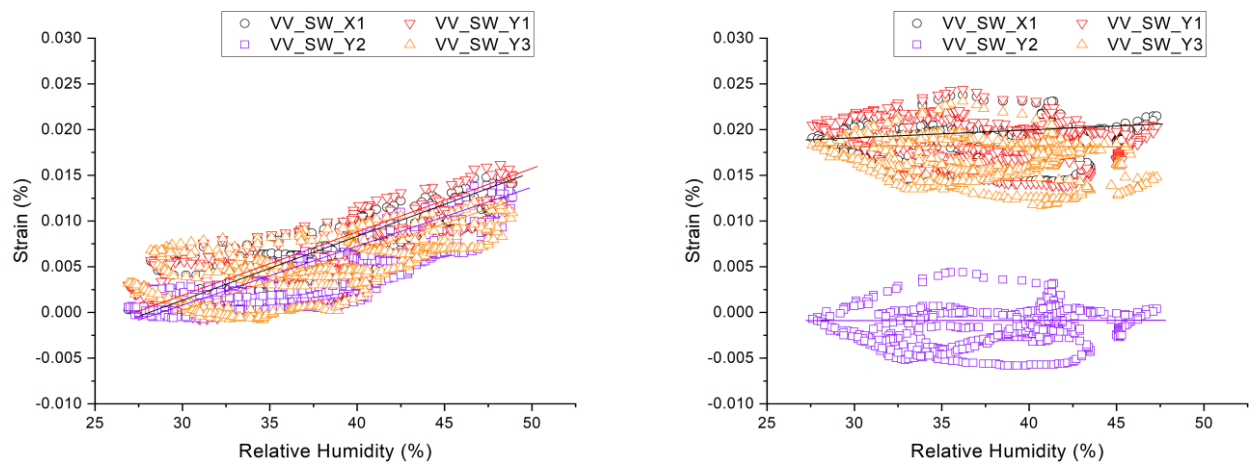


Figure 10-22: strain measurements of the Vickers Vimy starboard wing tear are before (left) and after (right patching) against Relative Humidity

Gauge Location	Rate of strain response to RH before patching	Rate of strain response to RH after patching	Response ratio before patching to lab control gauge	Response ratio after patching to lab control gauge
VV_MF_1X	9.60E-04	1.01E-03	1.60	1.69
VV_MF_2X	9.60E-04	9.74E-04	1.60	1.62
VV_MF_3Y	3.17E-04	9.26E-04	0.53	1.54
VV_MF_4Y	3.43E-04	4.90E-04	0.57	0.82
VV_PW_Y1	6.88E-04	1.12E-03	1.15	1.87
VV_PW_Y2	6.88E-04	5.58E-04	1.15	0.93
VV_PW_Y3	6.88E-04	6.69E-04	1.15	1.12
VV_PW_Y4	1.44E-03	1.32E-03	2.40	2.21
VV_SW_X1	6.95E-04	8.32E-05	1.16	0.14
VV_SW_Y1	6.95E-04	0.00E+00	1.16	0.00
VV_SW_Y2	6.33E-04	0.00E+00	1.06	0.00
VV_SW_Y3	6.33E-04	0.00E+00	1.06	0.00
Lab Control Gauge	6.00E-04	6.00E-04	1	1

Table 10-6: Response rate of strain of aircraft on display in *Flight* to changes in RH before and after patching of torn areas

10.4. Discussion

10.4.1. Laboratory Panels

The results of the laboratory strain gauges show that the effect of a tear opening in a doped-fabric panel is most pronounced at the crack tip, and that there is greater crack tip opening in the warp direction than in the weft. This is consistent with previous experimental work, which has demonstrated that the weft of the 9F1 Irish Linen used is much stiffer than the warp. Upon the crack tip opening, moreover, the overall strain was shown to increase with repeated cycling, indicating that further deformation of the material and opening of the crack tip was occurring, though the amount of change in strain at the tip did decrease with each cycle, suggesting that such deformation, if occurring was stabilising under the test conditions.

A further factor to also be mindful of after tearing is temperature, which had a noticeable influence on the strain response at the crack tip. A rise in temperature was observed to result in relaxation at the tip and an increase in strain, and a drop in temperature led to a decrease in strain, indicating that it was causing stiffening of the dope film. Further work is needed to isolate this variable more effectively from RH which remained the dominant factor in the response of strain under the test conditions used, and to account for other potential temperature

effects which may introduce error such as if there is a difference in the thermal expansion coefficient of the strain gauges and substrate.

The process of applying a doped-fabric patch had an impact upon the behaviour and nature of the doped-fabric skin to which it was applied. In the laboratory panels the act of applying the patch resulted in an increase in strain in the direction in which the tear was opening. This increase is likely the result of the dope film of the panel being softened by the solvents of the fresh dope being brushed onto the patch. This softening enables relaxation in this direction, and possible further opening of the tear.

The idea of the original dope film being softened by application of the patch is further supported by the decrease in strain in the direction normal to the tear opening observed in the Con1 panels. This decrease in strain occurs as the stiffness of the panel in the area of the patch decreases and undergoes an increase in tension, whilst surrounding areas are compressed as the compressive force of the dope film is redistributed across the panel.

As the dope dries, the reformation of the dope film and consequent contraction and stiffening of the patched area can be seen in the decreasing strain of the gauges parallel to the tear opening and the increasing strain of those normal to it. It is noteworthy that the strain measured in the normal direction was greater after patching than before the tear was introduced. This strongly indicates that the patch has caused further compression in the area over which it was applied, whilst the tension in the surrounding areas has been increased.

These two findings, the softening of the original dope film and the change in strain of the surrounding material both count against the use of doped-patches as conservation treatments. In the first issue, that of the dope film softening, this strongly suggests that the original dope film is wholly or partially dissolved when the patch is applied. This entails the mixing of the dope from the original substrate and patch likely combine, meaning that there is no clear interface between the two where the patch might be removed without damaging the original surface below.

As for the second issue, that of the increased tension of the surrounding material, this denotes an increased load acting in the material around the contracting patch. Although not quantified or mapped, the introduction of further stress into an aged, historic material is probably best avoided to minimise further tearing in other locations, especially given the reduced tensile strength of the historic material in comparison to modern doped fabric as established in the previous chapters.

It should be noted, however, that the evidence indicates patching was very effective for the function it was designed to perform, namely restoring a potentially airworthy craft to flying condition. The use of the doped-

fabric patch resulted in a near full regain of strain at the location monitored nearest the crack tip and in areas beyond it, suggesting that the repair made the panel equally, if not even tauter than it was prior to the damage. The strain at the crack tip, moreover, appeared to be decreasing still when monitoring ended, indicating that further contraction of the patched area was still taking place when the experiment was terminated.

The application of patches, moreover, resulted in subsequent RH cycles to behave in a comparable manner to doped-fabric without a tear, though a reduction in hysteresis was noted. Such behaviour is potentially desirable in a conservation treatment, because of a similar RH response between the repaired area and surrounding material. This assumes, however, that the modern doped material behaves in a comparable manner to a historic doped-fabric material, which was not demonstrated in chapter 9, where historic materials were shown to have a lesser reaction to RH cycles than modern doped panels, a further point which makes reconsideration of the use of doped-fabric patches necessary.

In the case of Con1 panels, where smaller patches were applied, the effect on the strain measured in the panels was much reduced compared to that of the large patches applied in Con2 type panels. All the Con1 type patches caused some contraction in the warp direction, i.e. parallel to the tear opening, indicating that the patches, despite their smaller size were effectively bonded to the substrate and having some influence on the tear, drawing the edges closer together. The Con1A patch, which covered the largest area of the tear, resulted in the largest contraction in the direction of the warp, followed by Con1B then Con1C respectively where relatively very little change was measured.

The strain in the direction normal to the tear in Con1 type patches also remained fairly consistent before and after patching, with no increase occurring in either Con1A or Con1B. The weft in panel Con1C may have crept, which seems likely a result of handling as the sharp drop in strain occurs in the period immediately around when it would have been transferred to the humidity chamber.

The reduced response of the panels to the effect of the patches trialled in Con1 type panels, indicates these are likely more suitable approaches for a historic doped skin aircraft compared to those used in Con2 and as currently practiced at the Science Museum, since they reduce the effect of any contraction caused by doping of a patch. They also cover a smaller area, and so removal would mean affecting a much smaller area of the original substrate. The use of doped fabric patches is, therefore, not in and of itself necessarily a poor choice, but careful thought as to the suitability of how and where it is applied needs to be given.

The results here are limited however, since it should be remembered that like is being compared with like in that fabric with known warp and weft characteristics is being repaired with the same type of fabric and dope. An

unaged material, in which different fabric directions may have different relationships and behaviours may not behave in a comparable manner, and further testing of different materials and techniques may yet show alternatives to be even more suited.

A final matter to be considered regarding the laboratory panels was the behaviour of Con1D, which was left untorn as a comparison to the other Con1 panels. In this case a continued, long-term contraction was measured beneath the more short-term responses caused by cycling of the RH. The cause of this long-term contraction could be a continued contraction of the dope, lending support to the long-term contraction of dope theories, though again the contraction showed signs of levelling off after several months, suggesting that the dope may take several months to dry, still well short of the years suggested in the literature.

There may, however, be other causes of the long-term contraction, such as creep of the panel if slippage of the panel was occurring, though this would not explain why the rate of contraction appeared to change depending upon the level of RH. The fact that the level of RH appeared to affect the rate of the contraction also suggests a potential experimental problem in acclimatising the panels to low RH conditions, in which the panels were not adequately acclimatised to low RH conditions but became more so with successive cycles.

The act of cycling the RH during the experiment may also have had an effect on the panel, with relaxing of the film at high RH enabling plastic deformations that allowed greater contractions on lowering the RH. The range of potential hypotheses show that continued dope drying should not be automatically assumed when long-term contraction is observed, and that further experimentation with drying panels at constant RH over longer time scales may be required to help understand the problem.

10.4.2. In-situ Patching on Flight

The complexity of moving from lab based experimental work to historic materials *in-situ* is evident in the monitoring of tears and patching of the Vickers Vimy. The behaviour of the Vickers Vimy fuselage in the width wise, X-direction, was consistent with the previous *in-situ* work in chapter 9, where the rate of response was similar, if slightly less than that found in the cockpit area of the fuselage with little or no hysteresis. A distinction in the lengthwise, Y-direction, between the two areas of the fuselage however, was clearly visible in the different response rates as around the tear there was very little response to RH, whereas at the cockpit end response had been almost equal between X and Y. This fits with the behaviour of the lab panels, in which the increase in strain at the crack tip over successive cycles of RH found to decrease.

The strain change on patching, moreover, in some respects agreed well with that expected from the lab panel results. The gauge nearest the crack tip measuring strain in the X direction registered an overall contraction of

about 0.04%, whilst those located slightly further away in both the X and Y directions measured a smaller contraction of about 0.02%. This suggests that, as in the lab panels, the patch on the Vimy fuselage had bonded effectively, and that the contraction of the panel was having an influence on the surrounding material with the greatest effect in its immediate vicinity.

In terms of the response rate to RH the biggest change between the patched and unpatched state was at the tear tip in the lengthwise, Y-direction where the response to changing RH became three times more sensitive to RH after patching, and was almost identical to the response of the gauges measuring strain in the width direction. The second gauge in the lengthwise direction also became more sensitive to RH after patching, by almost 1.5 times. This demonstrates that even after application, the patch may have a long-term influence on a local level not only due to the contraction of the dope, but due to changes in how it then also responds to RH. In this case, the patch appears to have been effective at returning the material to its previous state and one more representative of the fuselage as a whole, assuming that the strain response to RH measured in the cockpit area is representative of the fuselage as a whole.

It should be borne in mind, moreover, that construction differences between the fuselage and other surfaces, such as the wings and control surfaces exist, as the fuselage is only lightly restrained due to having been cross-sectioned. This may result in larger, more immediate responses to changes in RH due to the response of the restraining ropes, rather than the response of the fabric itself. The panels of doped-fabric forming the wings in contrast, are firmly attached to the structure, barring in the locations of tearing.

The response of strain to RH of the doped-fabric skins on the Vickers Vimy wings is less consistent compared to any material previously monitored. The relationship between RH and strain was found to be weaker than other historic areas monitored before patching, and was made even weaker by patching. This is likely attributable to a delay time measured between a change in RH and the subsequent response in the fabric. The influence of RH is likely therefore still important in determining strain changes in the doped-fabric, but its effect is retarded by some other property of the material.

Several factors or combination of factors, may contribute to this delay in RH response. Chemical changes in the doped-skin may have reduced the number of hydroxyl sites and thus reduce the rate of response to moisture. The presence of the paint layer may also limit penetration of moisture into the structure, though this would not be consistent with the results of the fuselage, which was assumed to be made of the same material and is also painted but did not appear to have a delay between RH change and strain response. Alternatively, the irregular shape and size of the tears, and any resultant deformations in the material which may have occurred over time

may have resulted in these areas becoming less restrained than in other locations studied, and so less likely to respond to RH fluctuations.

The application of the doped-fabric patches further retarded the effect of RH on strain by several hours in both the port and starboard wings. This was not the expected outcome as it was thought that a patch might increase the rate of response if the doped-fabric patch came to dominate the materials response to moisture. The patches could have several effects on the system to cause this change. By creating a barrier layer over the paint surface, they could further retard penetration of moisture, and thus slow the response of this stiffer material to moisture, thus reducing response rates further.

10.5. Summary

The results of the laboratory experiments show that patching does have an influence on the strain measured at a crack tip, and that applying a doped-fabric patch, whether over a large area as in Con2 panels, or smaller ones as used on Con1 type panels, can result in a reduction in strain at the crack tip. The size of the patch, however, does appear to have an important influence on the extent to which the crack tip is closed, with the size of the effect decreasing with smaller patches. The effect of the Con2 patches were also shown to extend beyond the edge of the patch into the surrounding material, causing increased strain in line with the direction of the tear growth, which was not measured in the case of the Con1 type patches.

The variations and variability of the environment in which *in-situ* measurements were undertaken made understanding these results much more complex, as there are a great many more factors potentially influencing the strain measurements which were not accounted for in the laboratory based experiments. These include local differences as to how the dope-fabric skin is secured in place, potential chemical changes due to ageing and a more complicated doped-skin structure due to the addition of paint layers. The application of the doped-patches, however, did appear to have some impact on the behaviour and response of the fabric in these locations, though the mechanisms by which it affected the object in such a complex environment would need more detailed study.

Finally, the drying of panel Con1D has demonstrated that dope films may continue to dry over a longer period than expected from earlier results of this study. Although dope films had appeared to largely stabilise after several hours drying, it appears that further contraction over several months may have continued, though there are several mechanisms besides that of the dope contraction that may account for this.

11. Conclusions

This project has explored the history, museum context and material properties of doped-fabric in order to better understand the doped-fabric aircraft collection and the doped-fabric patching technique used to conserve tears as currently applied at the Science Museum. It has identified that areas of concern hindering conservation decision making were a lack of knowledge about the doped-fabric aircraft at the Science Museum, both in terms of the wider historic context and the specific histories of the individual aircraft, and a lack of knowledge about the effect of applying doped-fabric patches, both in terms of its effect on the historic dope and the compressive force it exerts on the patched area.

This thesis has developed an effective methodology to measure the effect of doped-fabric patching by measuring the strain of the substrate using resistance strain gauges. This was applied both in a lab context using surrogate panels of modern doped-fabric and *in-situ*, monitoring historic doped-fabric aircraft on the Science Museum's *Flight* gallery. This work has shown that:

- Fresh dope being applied during application of a patch causes a dissolution and re-formation of the underlying dope layers of the substrate.
- The largest initial contraction of the dope film occurs over several days, but may then continue for several months afterwards at a much slower rate.
- Both the modern prepared panels of doped-fabric and historic doped-fabric skins exhibited a dimensional response to changes in Relative Humidity (RH), but the response of historic material was not identical to that of the modern materials studied.

Considered as a whole the outcomes of this thesis enables new approaches when thinking about the conservation of doped-fabrics and related objects in a static museum context, and provides a pathway for better decision making around treatments and monitoring.

11.1. Conservation Implications

This work has shown that the value of the current doped-fabric skins as historical records is limited, and there is a strong case to be made that retaining them in their current context should not be viewed as a significant priority. This is largely because the skins are museum re-coverings and, although the materials used in making them are generally consistent with traditional doped-fabric materials, their appropriateness in terms of the specific history and characteristics of each individual aircraft is questionable.

This has been demonstrated in the case of re-coverings where the accuracy of the finish, both in terms of the materials used and their appearance, cannot be linked back to material from previous coverings retained in the museum technical files. Alterations between current and earlier forms of the aircraft might include changes in the type of dope used (whether nitrate, acetate or acetate butyrate) as well as the type of fabric and the addition or removal of paint layers. Such changes may or may not result in an immediate aesthetic or visible change in the appearance of the object, but do detract from attempts to study the doped-fabric skins as pieces of historic evidence if attempting to understand how the aircraft might have been constructed and maintained when a functioning, flying machine.

Upon re-covering, many features that would have been unique and individual to the aircraft due to its history of manufacture and use, such as the quality of construction and the number and types of repairs carried out, were destroyed and are now inaccessible for study. The retention of small pieces of fabric in the technical files, therefore, whilst in some respects useful, provides only a small snap shot of the previous doped-fabric skin covering the aircraft, the value of which is then even further reduced due to the lack of context and documentation surrounding the history and significance of the technical file materials in their own right. The current doped-fabric skins, therefore, are of limited historical use and significance as their authenticity in terms of how accurately they represent potentially different versions of the aircraft over time cannot be established.

The current doped-fabrics, therefore, may be viewed as significant conservation records demonstrating how the Science Museum has tended to manage and interpret such objects, rather than as materials for studying and understanding historic doping practices during the objects' working lives. There is more to an object than historical accuracy, and there has been a clear change in the value and significance of the doped-fabric aircraft from when such objects were used as flying machines to their current incarnation as museum items. The most obvious alteration which manifests this change in value are the large cross-sections which have been cut into many of the doped-fabric skins. The insertion of a cross-section is drastic both visually and physically, making flight impossible and exposing areas of the aircraft for inspection that would have been invisible when operational.

Such significant change has occurred, however, because as museum objects the aircraft have an educational and curatorial value, being used for informing viewers and presenting a narrative about the development of historic aircraft structures and technology, as well as key events and aviation milestones. When deciding how to display the objects, therefore, some change in the appearance of the aircraft was considered acceptable by the curatorial staff for this purpose of re-interpreting the objects as educational tools about historic events and technological developments in aviation.

This accounts for how the Science Museum is utilising the aircraft, but more difficult to interpret and evaluate is the significance and value which the public and other interest groups currently read into such objects and may do in the future, especially in relation to museum interventions that viewers may not even be aware of. As discussed in the case of the Supermarine S6B, correspondence from the public shows that aesthetic considerations are important drivers influencing how objects are perceived and understood, but that there is a question mark about how well the individual histories of the objects are understood by the viewing public and how this might influence opinion (Chapter 3.1.3).

The cream/yellow paint layer of the Vickers Vimy, for example, which was likely added during the 1970's, may not be something museum visitors are aware has happened since the object entered the museum or consider of great interest. The paint layer therefore seems to have little value as there is no clear justification for its addition, and an argument could be made to remove it on the grounds of historical inaccuracy.

It is unknown, however, what reaction, if any, such a plan might be met with. The Vickers Vimy has been displayed in its painted condition for potentially forty years and in its current form is likely the only version of the object many visitors have ever known. A major alteration, therefore, could be met with opposition if it threatened visitors sense of familiarity and expectations as to how the object should look based on previous experience. The manner in which any major intervention was communicated and managed with the public, therefore, might influence its success as much as the skill and historical accuracy of the finished treatment, and this is something that should be borne in mind when making decisions and would require further investigation to better understand.

This raises the issue as to whether a re-covering or other major re-interpretation of the objects would necessarily be considered more 'original' or 'authentic' than that already present and, given the significant resources required when re-covering an aircraft, provides a strong argument to conserve and retain the aircraft in their current form for as long as possible. With every intervention made, moreover, there is a risk that anything of historic value and evidence which may still be present on the aircraft, whether that be due to the

retention of material from earlier recovering or faithful reproduction of these, will be altered or destroyed, and make interpretation of the aircraft even more complex and thus reduce the aircraft value as historic record further.

Despite the evidence for the later re-coverings and interventions occurring within the museum, therefore, there is still a case to be made for the retention and conservation of the doped-fabric skins for as long as possible in their current state, but the process of using doped-fabric patches should not be considered fit for purpose as currently practiced. Although it was found to be effective at re-tautening the fabric and closing the tear, the compressive force exerted by this new doped fabric patch has been shown to affect the surrounding material. In addition, given the greater tensile strength of the modern material forming the patch, and barring a failure of the bond between patch and substrate, any further failure in the object would seem most likely to occur elsewhere in the *historic* material rather than in the modern repair. The application of fresh layers of dope during patching, moreover, were found to affect the doped-fabric substrate, causing the historic dope film in this layer to soften and reform.

Such an intervention, which actively re-constitutes the underlying dope film and influences strain in the surrounding material, seems unwarranted when a range of alternative techniques, adhesives and materials are available for investigation that might be used without such effects. One alternative method investigated in this thesis was the use of smaller doped-fabric patches only at the tear tip to prevent further growth, and these were found to have less influence on the strain of surrounding material as well as reconstituting a smaller area of the historic dope due to the smaller patch area, making them preferable to the larger patches currently used.

There may be contexts, therefore, in which traditional repair materials are believed appropriate when smaller doped patches may still provide an option, especially since the effectiveness of other methods and materials, such as Japanese tissue and conservation adhesives, are still to be investigated. There is the further argument in favour of traditional doped-fabric patching in that it could have a role to play in the preservation of craft skills and traditional mechanical maintenance practice

There are several considerations, however, which count against these arguments in favour of doped-fabric patching. As noted above the context of the aircraft has changed from functional flying object to museum display piece, which has entailed certain changes in the appearance and display of the aircraft. Given these changes when moving the aircraft into to a museum context has clearly acknowledged they are no longer functional, working objects, it is not clear why the preservation approach should not also shift to acknowledge that the aircraft are no longer flying.

In addition, the application of patches as currently practiced, although based on traditional maintenance practices, is in some important respects altered since it does not involve sewing of the tear edges to strengthen the repair as was traditionally done, and is used in place of larger scale interventions, such as replacement of an entire panel, which might be considered necessary in some of the worst affected areas due to the extent of the damage. The application of patches, therefore, as currently used at the Science Museum, sits somewhere between the two approaches of conservation and traditional maintenance practice, satisfying neither and so should be abandoned.

Finally, this thesis, has drawn attention to the fragility of doped-fabric structures and the complexity involved in determining how such heritage should be managed and conserved. When considering large, seemingly 'indestructible' objects from technological and industrial collections, it is easy to overlook the potential conservation sensitivities and weaknesses inherent in them which can lead to unsustainable design decisions, and the doped-fabric aircraft at the Science Museum fall into this category.

Although designed to resist the rigours of flight, after decades spent in museum environments the tensile strength of the doped-fabric has decreased markedly compared to the modern material against which it was compared, suggesting it is much more vulnerable to damage from touching, as appears to be the case on the Vickers Vimy lower wing. This is not an easy problem to rectify given that moving the Vickers Vimy beyond easy reach would require significant resources, and alternative options, such as the use of barriers, may be met with resistance in museum spaces due to concerns for visitor flow and negative public perceptions of barriers. The significant decrease in tensile strength of the historic doped-fabric compared to modern samples, however, should act as a wake-up call as to how seemingly large and robust objects are still vulnerable to deterioration and failure on ageing, and as deserving of protection from preventable impact damage as any other historic material when presented in suitable museum display conditions.

This investigation, moreover, has demonstrated a relationship between the strain of doped-fabric (both modern and historic) to fluctuations in RH and, although not demonstrated conclusively here, a link between RH fluctuation and the failure mechanism of doped-fabric seems likely. Again, the effect of such environmental issues is widely recognised in the display and storage of many types of historic materials housed within museums, and this thesis provides conservators with evidence to advocate the same concern be given to the housing of historic doped-fabric aircraft. Of course, the large size of such objects makes the practicality of this more difficult since they cannot be placed in a sealed showcase micro-climate, and the question as to what constitute acceptable environmental parameters remains open to debate and further investigation.

12. Further Work

This project marks an initial starting point in a topic which deserves further study, and many outstanding questions remain. One of the main limitations restricting wider applicability of this study was that only one type of dope and aircraft fabric were used in constructing the doped-fabric panels intended to replicate the skin of historic aircraft in lab experiments, which were found to have different properties to that of the historic material, such as in load bearing before failure and response to RH. This limits the extent to which results from using such panels to investigate the treatment of tears may be extrapolated when considering treatments of historic materials, and areas for further study to address this may be split into three broad areas:

- Historical research into doped-fabric formulations and compositions
- The deterioration mechanisms of doped-fabrics
- The effect of alternative conservation treatments on tear stabilisation and strain in the surrounding material

Further historical research should be undertaken to deepen and clarify information regarding the materials used in making doped-fabrics in different areas and times. This project reviewed archival material at TNA primarily relating to WWI, but many innovations and developments, such as the use of iron oxide dopes and cellulose butyrate, developed after this period. Expanding this knowledge base would enable more critical judgements of doped-fabric aircraft skins to be made related to their historic context and make scientific analysis of historic samples of greater value when attempting to evaluate them.

Improved knowledge of doped fabrics, moreover, would aid in laboratory-based experiments in which simulated samples of doped-fabric were required, since improved knowledge of historic formulations could enable more accurate and representative doped-fabrics to be made depending upon the specific construction of interest. The analysis of strain monitoring might also be furthered through the application of other techniques, such as Digital Image Correlation (DIC) or Speckle Pattern Interferometry (SPI) with which to validate the performance of the strain gauge monitoring system.

The deterioration mechanisms of doped-fabrics was not examined in any depth in this project, but it has been assumed that similar mechanisms as identified in other research, for example the effects of acid hydrolysis and cyclic fatigue, may be contributing to the failure of doped-fabric. The approaches developed in this investigation may be used to further research into this topic, and would aid the conservation process through potentially identifying the mechanisms of most relevance to the failure of doped-fabric and thus the most effective steps to

stop or retard deterioration. Improved understanding of deterioration mechanisms could also enable the artificial aging of materials to better replicate the properties of aged doped-fabric skin for lab-based studies.

The combination of better understanding of the historic context and deterioration mechanisms would together enable the observed mechanical properties of the material to be related to its chemical composition. This improved knowledge would then enable the production of more representative laboratory surrogate materials for use when simulating tears and testing different conservation approaches, and enable more informed judgements to be made as to how different display, storage and conservation approaches might influence the properties of the material in the long-term.

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Appendices

A. List of Suppliers

- Strain Gauges:

Micro-Measurements

Vishay Measurements Group U.K. Ltd.

Stroudley Road

Basingstoke

Hants, Hampshire

United Kingdom

RG24 8FW

<http://www.vishaypg.com/micro-measurements/>

- Aircraft Dopes and Fabrics:

LAS Aerospace Ltd

Okehampton Point

Exeter Road Industrial Estate

Okehampton

Devon

EX20 1UA

United Kingdom

<http://lasaero.com/>

- Acrylic Sheetting:

PerspexSheet.uk

Unit 3

Magna Road Industrial Estate

South Wigston

Leicester

United Kingdom

LE18 4ZH

<http://www.perspexsheet.uk/>

B. Statistical values from Environmental Data collected in *Flight*

Year	Month	Mean (°C)	Standard Deviation (°C)	Minimum (°C)	1st Quartile (Q1) (°C)	Median (°C)	3rd Quartile (Q3) (°C)	Maximum (°C)	Interquartile Range (Q3 - Q1) (°C)
2015	Jan	18.75	1.37	14.90	17.60	18.90	20.00	21.70	2.40
2015	Feb	18.70	1.42	15.20	17.40	18.90	20.10	21.00	2.70
2015	Mar	19.37	1.08	16.50	18.50	19.70	20.30	21.40	1.80
2015	Apr	20.39	1.34	17.70	19.50	20.40	21.00	26.00	1.50
2015	May	20.79	1.23	11.30	20.00	20.70	21.60	24.00	1.60
2015	Jun	23.08	2.04	18.30	21.60	23.10	24.50	29.90	2.90
2015	Jul	24.60	2.04	20.60	23.40	24.30	25.70	32.70	2.30
2015	Aug	23.70	1.56	20.60	22.60	23.60	24.50	32.50	1.90
2015	Sep	20.90	0.80	11.00	20.40	20.80	21.30	23.60	0.90
2015	Oct	20.28	0.62	18.50	19.90	20.40	20.60	22.20	0.70
2015	Nov	19.85	0.76	17.10	19.50	20.10	20.40	21.30	0.90
2015	Dec	19.68	0.78	12.40	19.10	20.00	20.30	21.10	1.20
2016	Jan	18.81	1.29	15.60	17.75	19.00	20.00	21.00	2.25
2016	Feb	19.12	1.24	16.00	18.10	19.40	20.20	21.60	2.10
2016	Mar	19.36	1.14	15.90	18.40	19.70	20.30	21.30	1.90
2016	Apr	19.88	0.94	17.40	19.20	20.20	20.60	22.00	1.40
2016	May	21.79	1.87	18.10	20.40	21.60	22.80	27.30	2.40
2016	Jun	22.17	1.47	18.80	21.00	22.20	23.20	26.00	2.20
2016	Jul	23.64	2.28	19.90	22.10	23.20	24.70	32.00	2.60
2016	Aug	22.90	2.15	20.20	21.00	22.50	24.30	30.80	3.30
2016	Sep	22.09	2.11	19.40	20.60	21.30	22.90	29.80	2.30
2016	Oct	19.89	0.81	17.50	19.40	20.10	20.50	21.60	1.10
2016	Nov	18.71	1.14	16.00	17.90	18.90	19.70	24.30	1.80
2016	Dec	19.00	1.00	16.00	18.20	19.10	19.90	21.30	1.70
2017	Jan	18.77	0.99	15.70	18.10	18.80	19.60	20.70	1.50
2017	Feb	20.55	1.54	16.60	19.40	20.80	21.50	33.50	2.10
2017	Mar	21.57	1.78	18.20	20.30	21.40	22.80	26.50	2.50
2017	Apr	23.28	1.98	18.70	21.70	23.20	24.80	29.30	3.10
2017	May	23.77	2.50	18.90	21.90	23.60	25.20	31.10	3.30
2017	Jun	24.00	2.75	19.80	21.70	23.60	25.80	31.90	4.10
2017	Jul	24.23	2.20	20.20	22.60	23.80	25.40	32.50	2.80
2017	Aug	23.08	1.78	19.60	21.70	22.90	24.20	28.90	2.50
2017	Sep	21.05	1.04	18.50	20.40	20.90	21.60	24.50	1.20
2017	Oct	20.49	0.61	18.80	20.10	20.40	20.80	22.70	0.70
2017	Nov	19.77	0.78	10.90	19.20	19.90	20.30	21.60	1.10

Table 0-1: Statistical values calculated for temperature in *Flight*

Year	Month	Mean (%)	Standard Deviation (%)	Minimum (%)	1st Quartile (Q1) (%)	Median (%)	3rd Quartile (Q3) (%)	Maximum (%)	Interquartile Range (Q3 - Q1) (%)
2015	Jan	39.66	7.02	24.40	34.45	38.60	44.10	57.80	9.65
2015	Feb	39.06	5.88	23.20	34.70	39.20	43.30	55.70	8.60
2015	Mar	39.34	6.79	20.70	34.50	39.80	44.60	55.20	10.10
2015	Apr	41.10	6.82	21.40	36.50	42.00	46.10	56.20	9.60
2015	May	43.09	6.15	26.00	39.10	43.10	47.40	62.00	8.30
2015	Jun	43.41	6.91	26.20	38.80	42.40	48.00	62.70	9.20
2015	Jul	45.29	7.97	20.70	39.60	43.90	50.40	66.60	10.80
2015	Aug	50.90	8.37	29.40	44.80	50.00	57.90	72.10	13.10
2015	Sep	49.82	5.58	33.50	46.40	49.75	53.50	66.10	7.10
2015	Oct	51.57	6.90	37.10	46.70	50.60	56.20	72.60	9.50
2015	Nov	52.28	9.14	25.00	46.00	54.00	58.40	72.40	12.40
2015	Dec	51.55	5.04	35.20	47.90	51.20	55.70	62.80	7.80
2016	Jan	42.92	8.16	20.40	35.90	44.40	49.10	60.20	13.20
2016	Feb	37.74	7.59	22.40	32.00	36.65	43.60	55.40	11.60
2016	Mar	36.82	5.20	20.50	32.90	36.75	40.30	54.70	7.40
2016	Apr	36.60	6.09	19.50	32.60	36.40	40.90	56.30	8.30
2016	May	42.20	9.82	23.60	34.60	41.80	47.50	66.10	12.90
2016	Jun	54.26	6.94	33.50	50.80	54.00	58.70	73.50	7.90
2016	Jul	51.50	7.75	21.60	46.00	51.90	56.80	71.70	10.80
2016	Aug	54.45	9.24	30.70	47.20	55.40	61.25	78.00	14.05
2016	Sep	58.67	8.40	37.40	52.70	58.70	64.10	78.50	11.40
2016	Oct	51.31	5.42	34.20	47.70	51.20	55.60	62.00	7.90
2016	Nov	45.57	6.64	29.60	40.70	45.10	49.60	63.10	8.90
2016	Dec	46.53	5.93	31.20	41.80	47.00	50.60	59.80	8.80
2017	Jan	39.81	5.88	27.50	35.40	38.90	43.80	54.40	8.40
2017	Feb	40.49	6.65	27.00	35.30	40.00	46.50	54.30	11.20
2017	Mar	39.51	6.04	15.40	35.80	40.10	43.95	53.90	8.15
2017	Apr	32.83	4.69	17.90	29.90	32.90	35.80	44.50	5.90
2017	May	41.70	6.74	25.80	36.70	40.80	46.30	57.70	9.60
2017	Jun	48.84	6.56	32.60	44.30	48.80	53.50	65.40	9.20
2017	Jul	50.65	7.61	32.80	44.60	50.45	56.70	69.60	12.10
2017	Aug	50.52	8.51	27.70	44.30	50.10	55.80	75.40	11.50
2017	Sep	51.88	7.83	33.10	46.10	51.50	57.75	72.60	11.65
2017	Oct	52.65	9.58	32.20	44.90	52.60	61.40	70.00	16.50
2017	Nov	39.93	7.41	24.20	34.30	39.80	45.90	60.80	11.60

Table 0-2: Statistical values calculated for relative humidity in Flight

C. Underpinning Theory of Analytical Techniques

Fourier Transform Infra-Red

FTIR is based on the principle that different chemical bonds absorb energy of different wavelengths of infra-red light. For a chemical bond to absorb energy and move to a higher energy state it must contain a dipole moment. The dipole moment results in an electric field across the molecule, which can interact with the electric field component of the light wave at the same frequency. This means that IR spectroscopy is excellent for investigating those parts of a molecule where a dipole moment exists, but will be insensitive to any non-polar bonds which may exist.

A common analogy used for understanding the process of IR spectroscopy is modelling chemical bonds as springs which oscillate at a constant frequency. Bonds can be imagined as vibrating at a certain amplitude and frequency in a given state of excitation. When energy is absorbed, the molecule moves to a higher vibrational state, meaning its amplitude is increased but the frequency of oscillation remains the same.

The spring analogy allows the bond behaviour to be modelled according to Hook's law:

$$\bar{\nu} = \frac{1}{2\pi c} \sqrt{\frac{K}{\mu}} \quad [7.1]$$

Where $\bar{\nu}$ is the wavenumber, K is the force constant and μ the reduced mass

The key variables to calculate the theoretical wavelength of light a chemical bond will absorb at are therefore the weight of the atoms in the bond, and how 'stiff' the bond between them is determined by the force constant, K. The heavier the atoms or weaker the bond, the smaller the wavenumber that is theoretically calculated.

The Fourier Transform (FT) is a mathematical transformation applied to deconvolute individual wavelengths from an interference pattern created by two beams of light interacting. This is important for IR spectroscopy as without this technique, a sample would need to be exposed to each wavelength of light separately, making the process very time consuming.

FTIR, in contrast, enables information about all wavelengths in a desired range to be collected at once as they are combined to create an interference pattern which then interacts with the sample, and may subsequently be

deconvoluted. This speeds up the rate of analysis, and allows for multiple scans to be collected rapidly, improving signal to noise ratios.

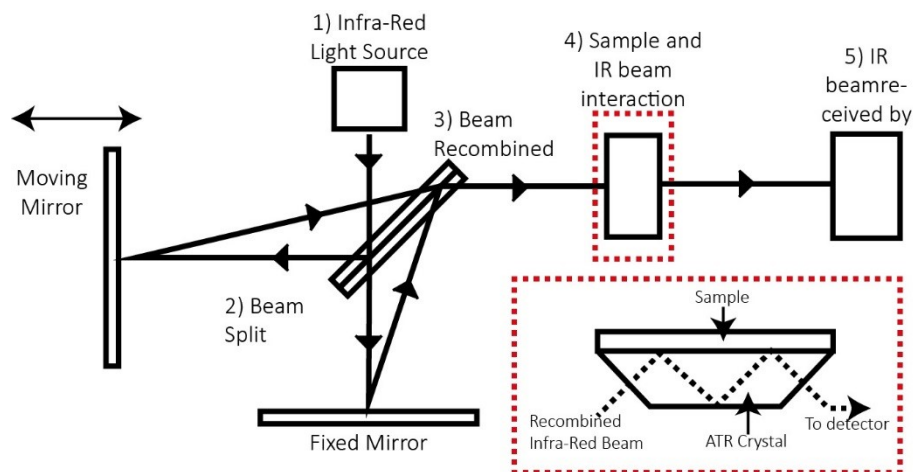


Figure 0-1 The stages involved in a Fourier Transform Infra-Red coupled with Attenuated Total Reflection

X-Ray Diffraction

XRD works by measuring the intensity of X-rays after they are diffracted by a crystalline substance. This is because once the X-rays are diffracted by the crystalline structure, they may either interact constructively or destructively with each other. Whether the X-rays interact constructively or not is governed by the different pathlengths X-rays must go through, which depends upon the inter-planar spacing of the crystal structure and the angle of incidence at which the X-ray interacts with the crystal planes. These factors are connected according to Bragg's law:

$$n\lambda = 2d \sin \theta \quad [7.2]$$

Where λ is the wavelength of the radiation, d the interplanar spacing between the crystal lattices, θ the angle of incidence and reflection, and n the phase difference between the incident and diffracted beam

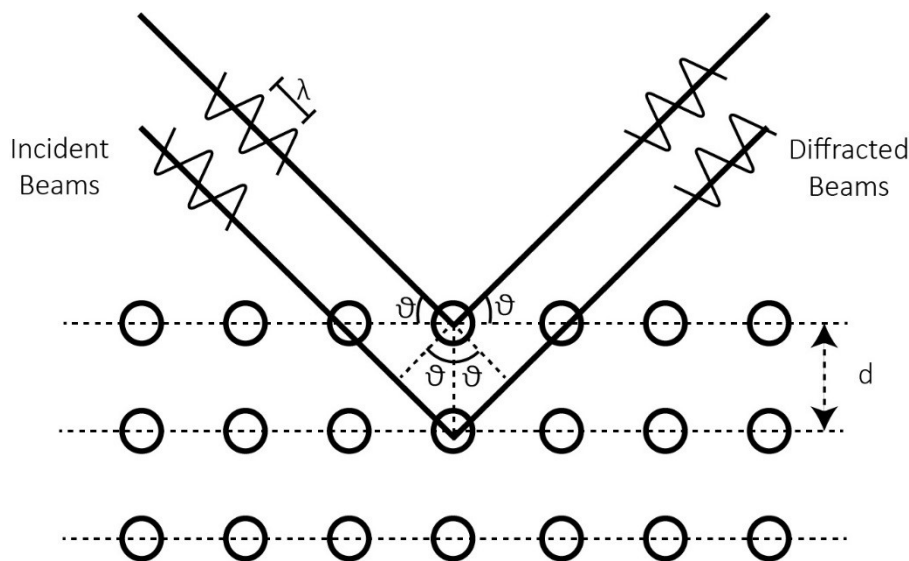


Figure 0-2 The conditions under which Bragg's Law may occur

It is possible by measuring the intensities of the diffracted X-rays at different angles, to reconstruct the crystalline structure and identify the compound responsible. X-ray diffractometers generally function either by maintaining the X-ray source and detector in a constant position relevant to each other whilst the sample rotates, changing the angle of incidence at which the sample interacts with the incident beam. Alternatively, the sample is kept in a constant position, whilst the incident beam changes through an angle of θ , and the detector moves through 2θ relative to the incident beam.

There are some potential limitations to the data that can be extracted using XRD. Accuracy of the diffraction pattern depends upon a flat sample being presented to the incident beam, and at the correct height in the machine for which the diffractometer is calibrated. This was not always straightforward with the historic samples available, where unevenness due to distortions of the fabric made this difficult to achieve across the entire sample surface. Sample thickness as for XRF is another issue, since the layered structure of these materials means it is not certain the depth to which X-rays may have penetrated and interacted.

X-Ray Fluorescence

XRF works due to the interaction of X-rays with the electron structure of atoms. The energy of an X-ray may be absorbed by an electron in a low energy level of an atom and, if it becomes sufficiently energetic, be emitted from the atom. When this occurs another electron from a higher energy level of the atom, will drop down to occupy the void left in the more stable, lower energy level. In changing energy states, from a higher level to a

lower level, this electron must release an X-ray, the energy of which is the difference between the energy levels of the two shells and is characteristic of the atom from which it is emitted.

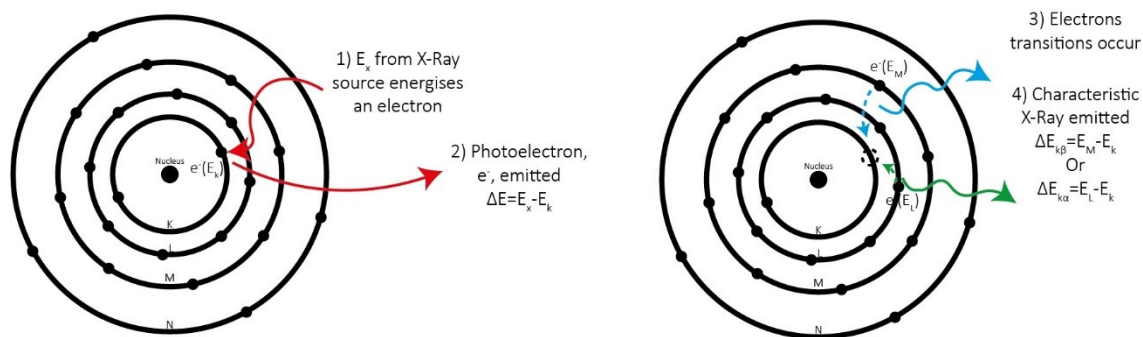


Figure 0-3: Examples of potential K-line electron transitions during X-Ray fluorescence

The energy levels of different atoms vary due to differences in the size of the nucleus and level of electron shielding between electron shells. The amount of energy released due to the re-arrangement of the electron structure is, consequently, unique to each element and the particular transition which occurs for each element. A single element, therefore, may produce multiple spectral emissions depending upon the number of orbital transitions that can occur.

Raman Spectroscopy

Raman spectroscopy functions due to the inelastic, Raman scattering of a monochromatic light source interacting with a sample. In Raman scattering, a photon is absorbed by a molecule causing it to enter a higher virtual energy state for a short period. Eventually, the molecule will emit a photon to return to a lower energy state.

For Raman scattering to occur, the polarisability of an atomic bond must be altered, i.e. the ease with which the bond may form a dipole or have its electron cloud density distorted. This is different to the case of Infra-Red spectroscopy discussed earlier, where it is the existence of a dipole itself that matters. A bond excited in Raman, therefore, is unlikely to be excited in IR spectroscopy and vice versa, meaning that the two techniques in combination provide different but complimentary information.

If there is a change in the rotational or vibrational state of the molecule on returning to a lower energy level, it will return to a different energy level from which it was initially excited, and this change will require it to absorb

or emit energy known as Stokes and Anti-Stokes Raman scattering respectively. The photon emitted during this transition will therefore have a higher or lower energy to that originally absorbed.

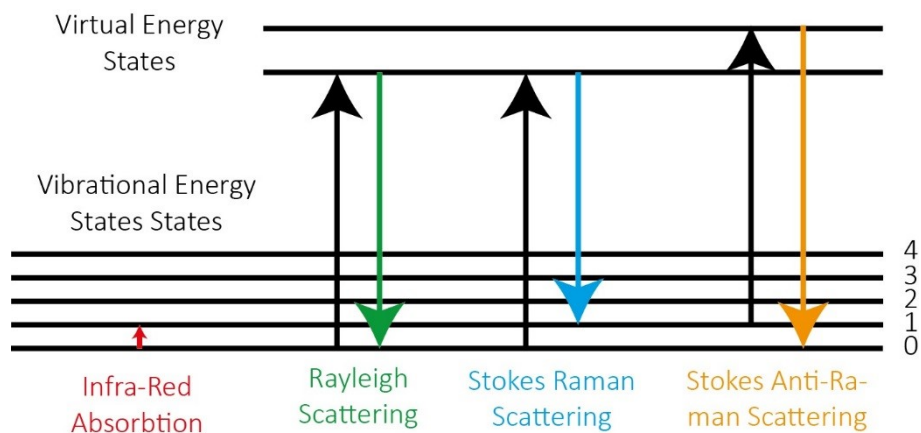


Figure 0-4 Potential scattering processes during Raman analysis