THE STATIC MECHANICAL PERFORMANCE OF REPAIRED COMPOSITE SANDWICH BEAMS: PART I - EXPERIMENTAL CHARACTERISATION

by

S MAHDI¹, A J KINLOCH², F L MATTHEWS³ & M A CRISFIELD⁴
IMPERIAL COLLEGE OF SCIENCE TECHNOLOGY and MEDICINE,
LONDON, SW7 2BX, UK

¹ *Mechanical Engineering Department & Centre for Composite Materials;
currently at CCM, University of Delaware, USA*

² *Mechanical Engineering Department*

³ *Centre for Composite Materials*

⁴ *Aeronautics Department*

ABSTRACT

The behaviour of undamaged and repaired CFRP sandwich beams loaded in four-point bending is described. Three repair configurations (one overlap and two scarf) were tested in tension and compression, and two repair systems (based upon either a relatively high and or low-temperature cure) were employed. It was found that the repair schemes tested recovered a very high fraction of the undamaged strength, although the ranking order of the configurations depended on the loading mode (i.e. tension or compression). The choice of the repair system did not have a major effect on the strength of the repaired CFRP beams.

1 INTRODUCTION

The potential to reduce the weight of structures, and increase fatigue and corrosion resistance, makes carbon fibre-reinforced plastic (CFRP) composites increasingly favoured as aircraft structural materials. A large amount of work has been done in connection with the design, construction and testing of these materials. Hence, as a result of an increased understanding of their behaviour, the relative weight of composites in aircraft has increased steadily in recent years. In the early 1970s, the Airbus A300 used a polymer composite in its fin leading edge and other secondary structures (i.e. a structure that would not lead to the loss of the aircraft if it were to fail). Later, in 1985, Airbus was the first manufacturer to use composite materials in commercial primary structure (i.e. a structure that would lead to the loss of the aircraft if it were to fail) with an all CFRP tail fin [1]. Today a significant amount of primary structure and nearly all moveable controls on the wings and the empennage, the cabin floor, and most of the service panels of modern airliners are made of composites. There are two main types of structure which are employed: monolithic stiffened or sandwich, chosen according to the detailed design requirements

However, the use of CFRP materials is limited by their poor delamination resistance which can cause severe reductions in strength and stiffness, and may lead to catastrophic failure of the structure. This characteristic can limit their use in some particular applications where damage is likely to occur. Thus, repair methods for in-service or

fabrication damage need to be developed to ensure that composite structures are economically viable.

In the current paper one aspect of a large programme on repair of CFRP structures [2] is reported. Here, the behaviour of undamaged and repaired sandwich beams, loaded statically in flexure, is presented. The present paper discusses the experimental characterisation of the beams, whilst in a companion paper [3] modelling predictions of their mechanical performance is discussed.

2 THE COMPOSITE SANDWICH BEAMS

2.1 Introduction

The beams were 700mm long by 200mm wide, with two-ply CFRP skins on a 15.8mm thick Nomex honeycomb core. The panel geometry and lay-up are shown in Figure 1. The skin material was a five-harness satin weave prepreg (F914C), composed of Toray T300 carbon fibres and Hexcel 914 epoxy resin, and manufactured by Hexcel (UK). One face had an inner [45/-45] ply (i.e. the fabric warp direction was at 45° and the weft direction was at -45°) and an outer [0/90] ply. This face, called the tool face (TF), contained the repair if present. The lay-up on the other face, called the bag face (BF), comprised two plies, of the same material, but both at [0/90] to ensure that failure occurs first on the tool face. A Hexcel Redux 319A adhesive was used to bond the skins to the core. The skins and core were co-cured and bonded together in one operation in an autoclave.

Figure 1: The sandwich beams

2.2 Materials

Satin weave cloths, as used for the skins, are not completely symmetrical because on one side of the cloth a high proportion of fibres are running in the warp direction (i.e. the fabric production direction), whereas on the other side a high proportion of fibres are running in the weft direction (i.e. the shuttle direction), and this leads to different warp and weft properties. In addition, the crimping of the fibres introduces different tensile and compressive properties [4]. The F914C prepreg cures in an autoclave at a pressure of 7bar and at a temperature of 175°C for 1hour, plus a 4-hour post cure at 190°C. The fabric areal weight of 285g/m² and a cured fibre volume fraction of 56%, leads to a cured ply thickness of 0.3mm.

The core was a phenolic resin impregnated aramid honeycomb (Hexcel HRH-10), with a cell size of 3.175mm and a density of 144kg/m³.

The Hexcel Redux 319A adhesive, which was used to bond the skins to the core, consists of a woven nylon-supported epoxy film.

2.3 Repair Procedures

2.3.1 Introduction

A series of tests, performed by BAe Airbus (UK), established that a 60mm diameter delamination ‘damage’ to the tool face would reduce the bending strength of the beam used in this work by 50% [5]. Repairs to a 60mm ‘damage’ area, that extended across the width of the TF only of the beams, were investigated in the present work. Removal of the ‘damage’ was simulated by cutting away a 60mm long strip of the TF skin centred at the mid-length of the beam. A literature survey [2] showed that overlap and scarf repairs were favoured repair methods, and their performance is assessed here under tensile and compressive loading. It should be noted that the tool face was chosen for the repair side since the lay-up of the TF is identical to that used in several applications by BAe Airbus. As commented above, the BF is of the same material, but with both plies at [0/90] to ensure that failure occurred first on the tool face which possessed the repair, if present.

2.3.2 Repair materials

Ideally repairs should be carried out using the original prepreg materials. In the field, however, these materials may not be available. Two repair systems were therefore evaluated:

High-temperature cure (HTC) repair system

A repair system identical to the parent materials was selected. The woven F914C prepreg was supplied by Hexcel. Hexcel Redux 319 unsupported tape adhesive was used to bond

repair patches to the parent. The patches were cured following the recommendations of the manufacturer, as described above, but under vacuum only.

Low-temperature cure (LTC) repair system

A 5-harness satin weave prepreg tape, supplied by The Advanced Composites Group (ACG, UK), was used as a low-temperature cure (LTC) repair system. The T300/LTM26EL woven prepreg and the XLTA225 repair adhesive were cured at 100°C for 4 hours, although they can be cured at lower temperatures but for a longer time. The prepreg, which comprised Toray T300 carbon fibres and LTM26EL epoxy matrix, had an areal weight of 285g/m² and a cured fibre volume fraction of 55%, leading to a cured thickness of 0.3mm.

2.3.3 Repair schemes

Three repair schemes were evaluated: one overlap patch repair and two scarf patch repairs.

Overlap patch repairs

Two-ply overlap repairs as shown in Figure 2 were produced. The patch resembles a four-ply laminate, but the two bottom plies do not play a significant role in the strengthening mechanism, they just fill the gap produced where the skin had been removed, and low density fillers are often used instead. The patch lay-up was chosen to be identical to that of the removed material (e.g. a [0/90, 45/-45] woven lay-up) so as to have a membrane stiffness close to that of the parent TF skin.

In order to keep peel stresses to a minimum, the normal recommendation is to have a ratio of at least 30 of overlap length-to-adherend thickness in the design of supported lap repairs [6]. The minimum overlap length, for a 0.6mm thick overlap, would therefore be 18mm. The thicknesses involved are however small and peel stresses are not likely to promote adhesive peel failure. Indeed, calculations, based on the Hart-Smith elastic-plastic analysis of bonded joints [2,6] showed that a 15mm overlap length should be adequate to carry a load equivalent to the strength of the skins in the present circumstances.

Scarf patch repairs

A scarf angle of 3° is often recommended in the design of scarf joints [6]. A conservative 1/30 scarf (i.e. a 1.9° angle), as shown in Figure 3, was initially used, but this requires the removal of a great deal of undamaged material. Thus, a 1/10 scarf (i.e. a 6° angle), as shown in Figure 4, that would remove less material, was also assessed in the present studies for comparison. Matching the parent and repair membrane stiffness has been shown to be important for scarf repairs and the patches were therefore made of two woven plies identical to the parent, i.e. a [0/90, 45/-45] lay-up. An overlapping ply was used to enhance the strength of the repair since, as discussed in reference [2], an overlap protects the tip of the scarf from being damaged. It is noted that repairs to thin structural elements do not leave much choice of lay-up to the designer, and a [45/-45] overlap ply was chosen, as it was felt that a [0/90] overlap would overstiffen the repair and create a

stress concentration in the vicinity of the patch. The final repair patch lay-up was therefore $[45/-45, 0/90, 45/-45]$. The same overlap length as for the overlap ply was kept for the scarf repairs (i.e. 15mm).

Figure 2: Two-ply overlap patch repair (dimensions in mm)

Figure 3: The 1/30 scarf patch repair (dimensions in mm)

Figure 4: The 1/10 scarf patch repair (dimensions in mm)

2.3.4 Manufacture of the repair patches

As already mentioned, the ‘damaged’ area, on the tool face of the beams, was machined away with a diamond coated cutter, leaving clear honeycomb cells exposed. A beam ready to be repaired with a scarf patch repair is shown in Figure 5. The repair area on the

skin was then grit-blasted and subsequently thoroughly cleaned with acetone. The prepreg and adhesive to form the patch were then applied directly over the prepared surface. It should be noted that in an actual repair the honeycomb core would also be typically replaced, either with new core or with a suitable foam material. However, in the context of the present work it was not considered that this extra step was necessary and thus only the CFRP face-sheet was repaired.

Figure 5: A beam ready to be repaired (scarf patch repair)

A perforated PTFE film (1 μ m perforations) was laid over the repaired area, together with a porous Melinex (ICI, UK) release film. The entire beam was covered in a breather cloth, and placed in a vacuum bag, as shown in Figure 6. All repairs were cured according to the recommendation of the manufacturer, but with vacuum pressure only to simulate ‘field’ repairs.

Figure 6: Repair procedure

3 EXPERIMENTAL PROGRAMME

3.1 Background

The specimens were tested in four-point bending. A total of twenty eight, 200mm wide, beams supplied by BAe Airbus were used in the present work [2]. The first part of the programme was concerned with the static characterisation of undamaged beams and widths of 30mm, 100mm and 200mm were tested. A width of 100mm was selected for the bulk of the work. Undamaged and repaired beams were then tested with the TF in compression or in tension. Load, deflection and surface strains were recorded up to failure. The number of specimens tested is presented in Table 1.

Table 1: Number of specimens tested

Beams	Compression	Tension
Undamaged - 30mm wide	1	1
Undamaged - 100mm wide	3	3
Undamaged - 200mm wide	1 + 10*	1
1/30 scarf HTC	2	1
1/30 scarf LTC	1	1
1/10 scarf HTC	1	1
2Ply overlap HTC	1	1
2Ply overlap LTC	1	1

** results communicated by BAe Airbus [5]*

3.2 The Flexural Test

The beams were tested using an ESH servo-hydraulic bi-axial fatigue testing machine. Load spreaders and rubber pads, 25 mm in width, were used at the loading points to prevent local indentation and failure of the skin and the core, as illustrated in Figure 7. The span between the outer and the inner loading points (Figure 7) was selected to promote skin failure. Figure 8 shows a view from above of a beam being tested. A PC equipped with a data acquisition system was used to record the test data (i.e. time, hydraulic ram deflection, load and strain). The time between which two consecutive data sets were recorded could be varied by the software. For instance, in static tests, data were typically sampled twice a second, continuously, until failure of the specimen. The individual points were then treated inside an 'Excel' spreadsheet.

Figure 7: Details of the four-point bending test

Figure 8: Four-point bending test

Strain gauges were used for the determination of surface strains. The application of gauges required preparation of the surface to which the gauge was to be applied, which included an abrasion stage (i.e. blasted with silica grit) and a cleaning stage (i.e. wiped with acetone). An epoxy adhesive was then applied to the carrier surface of the gauge and the gauge positioned carefully on the surface. Pressure, with the use of a soft rubber pad, was then applied overnight.

MEME CEA-06-125UN-350 strain gauges were used, with a gauge factor of 2.085 and a 350Ω resistance for a 6mm gauge length. The gauges were connected to $\frac{1}{4}$ -Wheatstone bridge amplifier (2.5V applied voltage). Strain measurements were taken on the longitudinal centreline of the specimens at several positions between the mid-length of the beam and one of the inner rollers.

3.3 Experimental Errors

A standard test will involve the application of the load to the rig and the measurement of corresponding deflections. Care must, however, be taken when measuring the deflections. Indentation of the skins at the load points and deformation of the rig means that a correction to the observed deflections should be considered, as described below.

A measure of indentation was obtained by placing a 200mm wide beam under simple through-thickness compression, up to a load of 10kN, and monitoring skin indentations. The indentation of the beam was measured with a travelling microscope set at the edge of the top skin of the beam. An indentation versus load curve was recorded and was relatively linear up to 10kN, at which load the beam was seen to indent by about 1 mm. It should be noted that the failure deflection of an undamaged 200mm wide beam is about 40mm. The indentation of the skin is therefore negligible and was ignored.

By measuring the deflection of a beam with a travelling microscope, and comparing this with the ram displacement displayed by the testing machine controls, a calibration curve was produced which allowed the former measurement (required for the calculations) to be obtained from the latter reading (i.e. that most easily obtained from a test).

4 RESULTS: UNDAMAGED BEAMS

4.1 Failure Load

In order to have a baseline for comparisons, the performance of undamaged beams was assessed by conducting tests on beams of various widths. The beams were tested with the TF in compression or in tension. The initial tests were done on ‘as-received’ 200mm wide beams. These tests were conducted in order firstly to validate the test rig, and secondly to understand the flexural behaviour of the beams. More tests were then conducted using 100mm and 30mm wide beams.

Experimental failure loads for the beams tested with the TF in compression and in tension are shown in Figure 9. Detailed results for the beams tested with the TF in compression are also shown in Table 2, whereas the detailed results for the beams tested with the TF in tension are shown in Table 3.

The static performance of ten undamaged beams, tested with the TF in compression, was investigated by BAe Airbus (UK) as part of a larger experimental programme [5]. The ultimate total failure load (UFL) was between 8000N and 10,000N, giving an average UFL per unit width in compression of 43.8N/mm width, with a standard deviation of

2.74N/mm. Results are summarized in Table 2. The beams failed from a compressive fracture of the TF, away from the loading points.

A single 200mm wide beam (CCND-6-204-6) was tested, in-house, under conditions similar to the BAe Airbus' beams. The beam failed at a load of 44.4N/mm (i.e. a total load of 8880N). This is only about 1% higher than the average failure load of the BAe Airbus' test results. The beam failed by compressive fracture of the TF, in the region between the inner loading points, i.e. in the region of constant bending moment. The surface strain at failure, measured at the centre of the TF, was -10,063 μ strain.

A single 200mm wide beam (CCND57) was also tested with the TF in tension, (see Table 3). The beam failed at a load of 50N/mm (e.g. a total load of 10,000N), by tensile fracture of the TF, away from the loading points. The surface strain at failure, at the centre of the TF, was 9000 μ strain. Additionally, on this beam, back-to-back strains (i.e. one gauge located at the centre of the TF, the other gauge located at the centre of the BF) were recorded (see Table 3). The results showed that the TF strains were higher than the BF strains as a consequence of the unsymmetric lay-up of the beams, indicating that the neutral axis of the beam was shifted away from its geometric centroid. A calculation, assuming that the strain distribution was linear through the depth of the beam, showed that the neutral axis was located some 1.3mm away from the centroid of the beam, towards the face of greater stiffness, i.e. the BF, which has a [0/90,0/90] lay-up [2].

In addition, when the strains measured at the centre of the TF beams tested with the TF in compression and in tension were compared, it was seen that for the same load, the TF in compression recorded higher strains than the TF in tension, i.e. by about 15% at failure.

A total of six 100mm wide beams were tested, three with the TF in compression and three with the TF in tension, with the results shown in Tables 2 and 3 and in Figure 9. The strength in compression is seen to be slightly higher than that in tension, with an average failure load of 47.9N/mm and 47.3N/mm, respectively, which is contrary to the observations made on the 200mm wide beams. However, the small number of specimens tested, in conjunction with the scatter in strength, prevents any firm conclusions being drawn. Thus, the static strength can be taken as independent of the loading mode. The beams failed in the same manner as the larger, 200mm wide beams, i.e. well away from the loading points. Furthermore, the TF strains at failure were close in value to the failure strains of the 200mm wide beams (see Tables 2 and 3). This was encouraging since it meant that the 100mm wide beams would be good candidates for the repair and fatigue programmes, allowing a doubling in the number of specimens available for testing from a limited stock of 200mm wide beams [2].

The lowest strengths were recorded for the narrowest, 30mm wide, beams, with failure loads of 43.3 and 41.3N/mm, for the TF in compression and in tension, respectively. These beams were not just marginally weaker than the wider beams, but they also failed under a loading point, for both loading modes. The strains at failure were also lower than expected, being -9087 μ strain and +7440 μ strain, respectively. The fact that the narrow

30mm wide beams failed prematurely underneath a load spreader clearly limits their use for repair and fatigue testing.

**Table 2 Test results for undamaged beams
(Tool Face in compression)**

Specimen designation	Specimen width (mm)	Failure load (N)	Failure load /Unit width (N/mm)	Failure strain (μstrain)
BAe Airbus*	200	8760 (549)	43.8 (2.74)	-
CCND6-204-6	200	8880	44.4	-10,063
201-4(1)	100	4800	48	-
CCND5-5(1)	100	4730	47.3	-10,513
CCND5-5(2)	100	4850	48.5	-10,129
C2	30	1300	43.3	-9087

BAe Airbus : Test results reported by BAe Airbus on 10 specimens [5], the figures in bracket are the standard deviations of the 10 test results.*

**Table 3 Test results for undamaged beams
(Tool Face in tension)**

Specimen	Specimen width (mm)	Failure load (N)	Failure load /Unit width (N/mm)	Failure strain (μstrain)
CCND57	200	10,000	50	+9000 / -7600*
CCND6-2(1)	100	4610	46.1	+9285
CCND3(1)	100	4980	49.8	-
CCND6-1(1)	100	4600	46	-
CCND6-6(3)	30	1241	41.3	+7440

*Failure Strain: The strain * was recorded on the bag face, opposite to the TF, which is in compression*

Figure 9: Ultimate failure load with respect to width of the specimens

4.3 Stiffness

As discussed below, the repair programme was undertaken using 100mm wide beams and therefore the bending stiffnesses of these widths of beams were studied. The bending stiffness (per unit width) of the 100mm wide beams was calculated from the (corrected) ram deflection measured from the crosshead movement. The bending stiffness of the beams, tested with the TF in compression and in tension, is shown as a function of the applied load in Figure 10. At low loads (i.e. between 0N and 1500N) the bending stiffness increases rapidly. This may be attributed to errors in the measurement of the deflections, as well as to the compression of the rubber pads. A plateau region, corresponding to the elastic response of the structure, is next seen, between 1500N and 3500N. There is good reproducibility of the results. A bending stiffness of $4.3 \times 10^6 \text{ mm}$ and $4.4 \times 10^6 \text{ mm}$ may be discerned for the beams tested with the TF loaded in compression and in tension, respectively. Finally, the stiffness decreases, probably due to damage effectively softening the beams, as the failure load is approached.

Figure 10: Bending stiffness: 100mm wide beams

The region between the inner loading points is supposedly subjected to a constant bending moment, which should result in a constant strain field in this region. This is confirmed in Figure 11 which shows a nearly linear variation with load of strain recorded at various locations.

Figure 11: TF axial strains: 100mm wide beams with the TF in compression

5 RESULTS: REPAIRED BEAMS

5.1 Failure Load

In this section the performance of the repaired beams is compared with that of undamaged beams. It should be noted that the failure load of the repaired beams (which were 100mm in width to maximise the number of beams available without comprising the failure load, see Tables 2 and 3) are compared with the failure load (UFL) of the 200mm wide undamaged beams. This baseline was chosen because the value of the UFL of the (smaller number of) 100mm wide undamaged beams was within the scatter band of the results for the 200mm wide undamaged beams, but the larger number of test results on the latter beams were considered to be the more statistically meaningful.

5.1.1 TF loaded in compression

Failure loads for the undamaged and repaired beams tested with the TF in compression are shown in Figure 12. The dashed line in Figure 12 represents the average ultimate failure load (UFL) of the 200mm wide undamaged beams tested with the TF in compression, i.e. 43.8N/mm.

Figure 12: The failure load of repaired beams: TF in compression

It may be seen that all repairs recovered more than 90% of the undamaged failure strength, with failure loads above about 40N/mm. Furthermore, it may be seen that the repair system, whether based upon a high-temperature cure or low-temperature cure system, did not have any significant effect on the static strength.

The 1/30 scarf repaired beams did not perform as well as the overlap repaired beams, with failure loads below the undamaged UFL of 43.8N/mm. On the other hand, the overlap repaired beams failed at loads higher than the UFL. These results go against the popular belief that scarf repairs are always stronger than overlap repairs [6]. However, the few specimens tested in the present work prevent the use of statistical tools, making it difficult to draw any firm conclusions.

The 1/30 scarf repaired beams, whether fabricated with a high- or low-temperature cure system, failed at a load of 40N/mm, therefore recovering approximately 90% of the undamaged (i.e. control) strength. The locus of failure of the HTC repairs was however different from that of the LTC repairs. The HTC scarf repaired beams failed outside of the repair patch (Figure 13), in the region between the loading points, whereas the LTC scarf repair beam failed in the repair at the overlapping ply/scarf junction (Figure 14). In both of these cases, this type of compressive failure appears to be a consequence of a local instability which results in fibre fracture.

Figure 13: Compressive failure outside the repair

Figure 14: Compressive failure inside the repair

The 1/10 HTC scarf repaired beam performed slightly better than the 1/30 scarf repaired beams with the failure strength above the control strength. The beams failed outside of the repair patch, as shown above in Figure 13.

Overlap repaired beams, whether with HTC or LTC repair patches, performed very well and failed above the failure load measured from the undamaged beam. The failure loci were however different for the two repairs. The HTC repair failed at the end of the

overlap at the parent/repair patch junction (Figure 15), whereas the LTC repair failed outside of the repair patch (Figure 13). Again, the failure shown in Figure 15 appears to be a consequence of a local instability which results in fibre fracture.

Figure 15: Compressive failure at the parent/repair patch junction

The far field strains at failure in the repaired beams (i.e. strains in the parent skin, away from the repair patch) varied from beam to beam, but were generally lower than the strains at failure recorded on the undamaged beams.

5.1.2 TF loaded in tension

The performance of repaired beams tested with the TF loaded in tension are compared in Figure 16. The dashed line in Figure 16 represents the average ultimate failure load (UFL) of the 200mm wide undamaged beams tested with the TF in tension, i.e. 50N/mm.

Figure 16: The failure load of repaired beams: TF in tension

Again, the repaired beams performed well and most repairs restored more than 90% of the control strength (i.e. the value of 50N/mm for the 200mm undamaged UFL in tension), the exception being the 2-ply HTC overlap repaired beam.

When loaded in tension the scarf repairs were seen to perform as well as, if not better than, the overlap repairs. The 1/30 HTC and LTC scarf repaired beams failed at a load of 45.3 and 49.5N/mm, therefore recovering about 95% and 100% of the control strength, respectively. These beams failed outside the repair area, by tensile fracture of the parent skin (Figure 17). The 1/10 HTC scarf repaired beam performed as well as the 1/30 scarf repaired beams and recovered 100% strength.

Figure 17: Tensile failure outside the repair (sketch for an overlap repair is shown)

On the other hand, the overlap repaired beams did not perform as well as the scarf repairs, with failure loads about 25% and 10% below the control strength for the HTC and the LTC overlap repaired beams, respectively. Thus, the 2-ply LTC overlap repaired beam recovered 90% of the control strength and failed outside the repair (Figure 17). On the other hand, the 2-ply HTC overlap repair failed at the end of the overlap at the parent/repair patch junction (Figure 18), and only recovered about 75% of the control strength. A possible reason for these observations may be an increase in the local stress and strain concentration resulting from the stress transfer at the end of the overlap [3,7].

Figure 18: Tensile failure at the parent/repair patch junction

5.2 Stiffness

The bending stiffnesses of the repaired beams tested with the TF loaded in compression are compared with that of an undamaged beam in Figure 19. It should be noted that the undamaged beam used for the comparison of the results is 100mm in width, since a 200mm wide beam would invariably be stiffer due to a cross-wise bending moment arising from the Poisson's contraction. This effect would make the results not comparable.

It may be seen that the repaired beams are stiffer than an equivalent undamaged beam. The bending stiffness of the repaired beams lies between about 4.4×10^6 and 4.5×10^6 Nmm, while that of an undamaged beam is 4.3×10^6 Nmm. The repaired beam would, of course, be expected to be stiffer than the undamaged one, since the overlapping plies make the repaired beams locally thicker.

Similar results may be seen for the beams tested with the repairs in tension in Figure 20. The repaired beams are generally stiffer than an equivalent undamaged beam (i.e. 4.7×10^6 Nmm compared with 4.4×10^6 Nmm). However, the bending stiffness of the 1/30 scarf repaired beams is now relatively low and similar to that of the undamaged beam, at about 4.4×10^6 Nmm. Again, the repaired beams would be expected to be stiffer than the undamaged beam, although it is not clear why the behaviour of the scarf repaired beams with the repaired TF loaded in compression differs from that when the repaired TF is loaded in tension.

Figure 19: Bending stiffness: repaired beams tested with the TF in compression

Figure 20: Bending stiffness: repaired beams tested with the TF in tension

6 DISCUSSION

6.1 Strength of Repairs

Figure 21 shows the failure loci and loads for the 100mm wide repaired beams tested with the TF in compression and tension and it may be concluded that most repairs were successful. It should be noted that the present repairs were designed following the rules described in the open literature [6]. The strength restored was in excess of about 90% of the undamaged strength in most cases and many repairs restored more than 100%, whether the repairs to the tool face were loaded in compression or in tension.

Figure 21: Summary of static failure loci and loads

(For comparison the undamaged 100mm wide beams failed at 4800N and 4730N for the beams tested with the TF in compression and in tension, respectively.)

The lowest failure load was recorded for the 2-ply HTC overlap repaired beam tested with the repaired TF in tension, and this repair recovered only 75% of the undamaged strength. However, it may be noted that a value of 75% of the undamaged failure load is still well above the operational load that would be seen by such a component in service, where the strains are typically limited to $\pm 4000\mu\text{strain}$. This strain is equivalent to a load of about 2000N, whereas the 2-ply HTC overlap repaired beam tested in tension still failed at load of 3600N.

6.2 Failure Loci

Firstly, and above all, it should be noted that all the loci of failure were located away from the loading points, which is a successful result for the testing method.

Secondly, most repaired beams failed outside the repair patch, recovering more than 90% of their respective control strength as noted above. Only the 1/30 LTC scarf repaired beam tested with the repair in compression failed inside the repair.

Thirdly, the repair system undoubtedly had an effect on the failure loci of the 2-ply overlap repairs. The HTC overlap repaired beams failed at the parent/repair patch junction, whereas the LTC overlap repaired beam failed in the parent skin away from the repair. Also, the choice of repair system had an effect on the loci of failure of the 1/30 scarf repaired beams tested with the TF in compression: the 1/30 HTC scarf repaired beams failed in the parent, whereas the 1/30 LTC scarf repaired beam failed inside the

repair at the overlapping ply/scarf junction. The reason why the repair system affected the failure loci is unclear, but it could be that because the HTC and LTC repairs have different material and geometric characteristics, these may have an effect on the detailed failure mode. For example, from microscopy studies it was found that the adhesive layer was clearly visible in HTC repairs, but not in LTC repairs where it seemed to have merged with the repair patch [2].

6.3 Repair Systems and Schemes

Firstly, it should be noted that the choice of repair system, being either a high- or low-temperature cure system, did not have a major effect on the static strength of the repairs.

Secondly, from the literature [6] it is reported that scarf repairs are usually found to be stronger than the equivalent overlap repair. This arises because the scarf geometry (a) results in a smoother load transfer when compared with the abrupt, step-like, change in geometry introduced by the overlap repairs, and (b) reduces the eccentricity of the load path in the repair. Indeed, when the repaired TF was loaded in tension, the scarf repaired beams were found to be slightly stronger than the overlap repairs. However, when tested with the repaired TF in compression, the overlap repaired beams were found to be somewhat stronger than the scarf repaired beams. The scarf repaired beams were now found to recover only about 90% of the control strength, in comparison with the full, original, undamaged strength which was recovered by the overlap repaired beams. Since the scarf repaired beams tested in compression mostly failed outside the repair patch, it is uncertain if (a) the lower failure loads were caused by the presence of the repair, or (b) these relatively low failure loads were just an artefact of the scatter in strength (i.e. it was the undamaged beams that were used which were inherently weaker, not the scarf repairs). However, it may be noted that the failure load of the beams tested with the TF in compression, increased as the scarf angle increased, and therefore as the repair area decreased.

6.4 Bending Stiffness

It was shown above that the bending stiffness of repaired beams, whether tested with the TF loaded in compression or in tension, were generally stiffer than the corresponding undamaged beams. An exception was the 1/30 scarf repaired beams tested with the TF in tension.

The overlap repaired beams were all stiffer than the equivalent undamaged beams, whether tested with the TF loaded in compression or in tension. The overlap patches are made of two plies, with an orientation identical to the plies removed on the TF. The excess of material in the overlap, which transfers the load from the parent to the patch, and the eccentricity of the patch from the parent surface, contribute to the increase in stiffness of the beams; whether the repairs are loaded in tension or in compression.

The scarf repaired beams were seen to be stiffer than, or have the same stiffness as, the corresponding undamaged beams. The behaviour of the 1/30 scarf repaired beams was

seen to be different whether the repaired TF was loaded in compression or in tension. The reason for this is unclear as it may be thought that the effect of the repair patch on the stiffness of the beam should be the same, whether the beam is loaded with the TF in compression or in tension. It may, however, be observed that the repair patches are located on the same side as the inner loading points when the TF is in compression, whereas they are on the opposite side when the beams are tested with the TF in tension. The edge of the 1/30 scarf, 1/10 scarf and 2-ply overlap repairs are located 62mm, 74.3mm, and 80mm, respectively, from a loading point. It may be that the proximity of the load spreaders to the repair patches influences the flexural behaviour of the beam more when the TF is in compression than when it is in tension. It may also be noted that the anticlastic curvatures are in the opposite direction when the repair is in compression or in tension, thus causing the beam to bend towards, or away from, the loading pads, as indicated in Figure 22.

Figure 22: Schematics of the repair in compression or in tension

7 CONCLUSIONS

The performance of scarf and overlap repaired beams with their repaired tool face (TF) loaded either in compression or in tension was assessed. From the present work it is concluded that:

- The static strength of the undamaged tool face was essentially the same whether loaded in compression or in tension.
- The repair schemes used in the present work were found to be very successful. Most repairs failed at a load above 90% of the undamaged failure load, therefore recovering most of the load-carrying capability of the structure.

- The loading mode (i.e. compression or tension loading on the repaired TF) did, in some instances, have a significant effect on the observed behaviour of the repaired beams.
- In compression, the scarf repairs were found to be weaker than overlap repairs; the former achieved only about 90%, whereas the latter achieved 100%, of the undamaged strength. Conversely scarf repairs were stronger in tension: achieving 100% of the undamaged strength, with the overlap repairs now only showing about 75% of the undamaged strength.
- The repair system, being either a high- or low-temperature cure system, did not have a major effect on the strength of the beams.
- The loci of failure for the undamaged and repaired beams was in the region between the two inner loading points and away from the load spreaders. Most repaired specimens failed well outside of the repair patch region, except for (a) the 1/30 LTC scarf repair loaded in compression which failed in the repair, and (b) the 2-ply HTC overlap repairs which failed at the end of the overlap at the parent/repair patch junction.
- The bending stiffness of repaired beams, whether tested with the TF loaded in compression or in tension, was generally higher than the corresponding undamaged beams. An exception was the 1/30 scarf repaired beams tested with the TF loaded in tension which had the same stiffness as the undamaged beams.

ACKNOWLEDGEMENTS

Funding by EPSRC is gratefully acknowledged. Many thanks go to BAe Airbus, BAe Systems, DERA, Hexcel, FEA Ltd., GKN WHL, GKN Aerospace and NPL for sponsoring this project and for supplying materials, structures and advice. The authors would like to thank Mr. H. MacGillivray for his assistance with the experimental studies. Sadly, Professor M. Crisfield died during the preparation of the present paper. His friendship and scientific contributions will be greatly missed.

REFERENCES

- [1] D. H. Middleton, *Composite Materials in Aircraft Structures*: Longman Scientific and Technical, 1990.
- [2] S. Mahdi, "The Performance of Bonded Repairs to Composite Structures": PhD Thesis, Imperial College, London, February 2001.
- [3] S. Mahdi, A. J. Kinloch, F. L. Matthews and M. A. Crisfield, "The Static Mechanical Performance of Repaired Composite Sandwich Beams: Part II – Finite Element Modelling". *The Journal of Sandwich Structures and Materials*. To be published.
- [4] S. M. Bishop, "Strength and Failure of Woven Carbon-Fibre Reinforced Plastics for High Performance Applications" in *Textile Structural Composites*, T.-W. Chou and F. K. Ko, Eds.: Elsevier, 1989.
- [5] G. McBroom, "Interim Report: Allowable Damage Investigation, Carbon Composite Structures" BAe, Airbus, Bristol, UK, Report Number: R7T, B4503,22774, 1997.
- [6] L. J. Hart-Smith, "Design of Adhesively Bonded Joints" in *Joining Fibre-Reinforced Plastics*, F. L. Matthews, Ed.: Elsevier Applied Science, pp. 271-311, 1987.
- [7] A.J. Kinloch, *Adhesion and Adhesives: Science and Technology*, Chapman & Hall, 1987.