

Investigation on the mechanical behaviour of single-lap composite joints with countersunk bolts

by

Cesare Stocchi

Imperial College
London

Department of Aeronautics
Imperial College London
SW7 2AZ

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Abstract

In this thesis, the mechanical behaviour of 2-bolt single-lap CFRP joints with countersunk bolts is investigated, both numerically and experimentally.

A detailed 3D non-linear FE model of composite bolted joints has been developed. The model replicates with good agreement the experimental tensile tests up to the point where bearing damage occurs and reproduces the joint behaviour correctly. Five stages are identified in the joint behaviour. The evolution of contact during the test is studied showing a correlation with the joint stiffness. Parametric studies investigate the influence of bolt clamping force, coefficient of friction and bolt-hole clearance on the joint behaviour.

Using the developed FE model, the distribution of the six stress components around the holes of the composite joints is studied together with the effects of head height, shank-hole clearance and position of bolts. The stress along the fibres is identified as the critical stress component and the compressive fibre failure of the 0° oriented plies as the start of the bearing damage. The 0° oriented plies in the cylindrical part of the hole are found to be the plies carrying the bearing load. Increasing clearance reduces the extent of the bolt shank-hole contact and leads to higher stresses and lower joint stiffness. The 45° and -45° oriented plies are found to have a key role in the joint bearing strength and shear-out failure.

Fatigue tests are run with the introduction of a novel method to monitor the loss of clamping force and detect crack initiation in the fasteners during the test itself, using strain gauges and a real-time algorithm. The clamping force is found to remain

ABSTRACT

constant until crack initiation and progressively drop until final failure. Load transfer and interaction between the bolts is observed during the fast but stable fatigue crack propagation. The fatigue tests are conducted on joints with differing plate thicknesses and countersunk head geometries to assess the influence of these on the number of cycles to crack initiation and to final failure. A link between fatigue and static test results is highlighted and, in addition, a fatigue failure mechanism of the joint is proposed.

Declaration

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Notation

Lower case Roman letters

d	<i>Bolt shank diameter</i>
e	<i>Distance from plate hole axis to plate run-out</i>
t	<i>Plate thickness</i>
w	<i>Distance from plate hole axis to plate edge</i>

Upper case Roman letters

CFI	<i>Clamping Force Index</i>
E_1	<i>Longitudinal modulus</i>
E_2	<i>Transversal modulus</i>
E_3	<i>Through- thickness modulus</i>
G_{12}	<i>In-plane shear modulus</i>
G_{13}	<i>Transverse shear modulus</i>
G_{23}	<i>Through-thickness shear modulus</i>
R	<i>Minimum to maximum load ratio</i>
S_{12}	<i>In-plane shear strength</i>
S_{13}	<i>Transverse shear strength</i>
S_{23}	<i>Through-thickness shear strength</i>

NOTATION

X_T	<i>Longitudinal tensile strength</i>
X_C	<i>Longitudinal compressive strength</i>
Y_T	<i>Transverse tensile strength</i>
Y_C	<i>Transverse compressive strength</i>
Z_T	<i>Through-thickness tensile strength</i>
Z_C	<i>Through-thickness compressive strength</i>

Lower case Greek letters

α	<i>Angle around plate hole</i>
ϑ	<i>Countersunk head angle</i>
σ_1	<i>Longitudinal stress</i>
σ_2	<i>Transversal stress</i>
σ_3	<i>Through-thickness stress</i>
τ_{12}	<i>In-plane shear stress</i>
τ_{13}	<i>Transverse shear stress</i>
τ_{23}	<i>Through-thickness shear stress</i>
ν_{12}	<i>Major Poisson's ratio</i>
ν_{13}	<i>Major transverse Poisson's ratio</i>
ν_{23}	<i>Through-thickness Poisson's ratio</i>

Chapter 1

Introduction

1.1. Motivations

Bolted joints have been extensively used on aircraft since the dawn of aviation and, even with the recent and widespread introduction of composite materials, still play a key role in aeronautical structures. In addition to high stiffness and strength, this technology offers the possibility to disassemble the joint for inspection and maintenance or to access concealed parts of the structure.

The increased amount of composite material used in the latest generations of aircraft has not changed the importance of bolted joints in the aeronautical industry. However, it has presented new challenges to address and new possibilities to explore. On the one hand the failure process in composite materials can be far more complex to understand and simulate than in metals. On the other hand, composite materials offer far more flexibility in material and part design, as well as a better fatigue behaviour.

The fastener shapes currently used with composite plates are, in most of the cases, directly derived from the ones used with metal plates. With aluminium plates,

the final failure is often caused by excessive bearing damage and hole elongation, both under static and fatigue loading. Since carbon fibre reinforced plastic (CFRP), in the fibre direction, has higher static and fatigue strength than aluminium, using CFRP plates in joints, with the same dimensional ratios as with aluminium, may lead fastener failure to be a typical joint failure mode.

To improve the performance of joints, a deeper understanding of the joint behaviour is needed. The mechanical response of composite bolted joints can be complex due to the interaction between the several parts, the inherent complexity of composite materials and the high number of parameters known to influence the behaviour. The mechanical behaviour could be studied with a large amount of experimental tests, which could be both time consuming and very expensive, or, more efficiently, with an integration of selected experimental tests and sufficiently accurate and flexible finite element models.

1.2. Literature review

1.2.1. Overall literature review

Countersunk fasteners are used in aeronautical structures in great quantities since they are needed where a joint surface is exposed directly to the aerodynamic flow and drag reduction is demanded. In this case, a single-lap configuration is typically used, even if this usually exhibits lower strength than a correspondent double-lap configuration [1, 2]. Most of the published works focus on double-lap joints, being simpler to study, with less severe stress concentrations and without the typical secondary bending observed in single-lap joints.

The main standard covering the study of composite bolted joints and bearing testing is ASTM D5961/D5961M – “Standard Test Method for Bearing Response of Polymer Matrix Composite Laminates” [3] which defines the main terminology of the

field and provides guidance on experimental testing, including the tests on single-lap joints with countersunk fasteners. To extend these concepts to fatigue testing ASTM D6873/D6873M – “Standard Practice for Bearing Fatigue Response of Polymer Matrix Composite Laminates” [4] has been produced. In addition to this, ASTM D7248/D7248M – “Standard Test Method for Bearing/Bypass Interaction Response of Polymer Matrix Composite Laminates Using 2-Fastener Specimens” [5] defines the bearing/bypass interaction and the corresponding testing setup for a two fastener joint.

The main failure modes [2, 3] that a composite bolted joint may experience are bearing, cleavage, net-tension (or net-section), shear-out, tear-out, bolt pull-through and various types of fastener failure. The occurrence of a specific failure mode rather than the others is strongly influenced by the geometrical ratios in the joints [6-8]. If the joint is properly designed, net-section and bearing are usually the main failure modes for the composite plates. Even though both can occur at high loads, net-section is characterised by a sudden loss of joint stiffness, resulting in a brittle failure. Bearing, instead, exhibits a gradual loss of stiffness and a much bigger joint elongation before final failure, resulting in a ductile failure. For this reason bearing is considered the most desirable joint failure mode for the composite plates.

1.2.2. Numerical simulation of the mechanical behaviour of composite bolted joints under static loading.

In the past, a significant amount of research has been published regarding the numerical and experimental study of the composite bolted joint behaviour. Several approximate but time-efficient numerical models have been presented. Several researchers [9-12] developed a 1D finite element model composed of structural elements with the possibility of simulating the effects of bolt clamping, clearance and friction. Several 2D FE models have also been developed to study the joint behaviour. In these works the pins are generally modelled as rigid surfaces while the plates are

represented as shell elements [13-14] or continuum shells [15]. Despite being quick and useful for the joint design, these approaches do not enable the study in depth of the complex interaction between bolts and plates because the through-thickness dimension of the joint is not represented.

Ireman [16] in 1998 highlighted the need for a 3D FE model for a detailed study of the behaviour, strength and stress distribution in composite bolted joints. He developed a model for the study of composite joints with protruding or countersunk bolts using a combination of solid elements. The bolt preload was applied iteratively defining an orthotropic thermal expansion coefficient in the bolt shanks and then by changing the temperature at the beginning of the simulation. Tserpes et al. [17] improved Ireman's model including the clearance between bolts and holes in the study of joints with protruding fasteners. More recently Hühne et al. [18] presented a 3D model of a single lap, single bolt composite joint with the aim of studying the effect of the liquid shimming between the plates on the joint behaviour and strength. Other researchers [19] developed 3D models to investigate composite bolted joints. All these researches showed the potential for a sufficiently detailed 3D FE model to capture the local and global effects of geometrical features and parameters on the joint mechanical response.

Several attempts have been made to study numerically and experimentally the effects of geometrical features and parameters on the joint behaviour and strength. Ekh et al. performed a numerical investigation of the effect of the distance between bolts on the secondary bending and strength of the joints [20] and an analysis of the load transfer in multi-row bolted joints [21]. Similar researches were performed in [22-24]. Several researchers [25-39] performed extensive investigations on the effect of clearance on the joint mechanical response. McCarthy et al. studied the phenomenon experimentally using single lap joints with single finger-tight protruding bolts and showed a delay in the load take-up proportional to the amount of clearance between bolts and holes [40-41]. After this they aimed to replicate the observed behaviour with a 3D FE model [42] with the same joint configuration and no preload in the bolts. This

model was able to reproduce the clearance effect seen in the experiment with good accuracy. They therefore extended the model to study the clearance effect in multi-row bolted joints [43]. Since all these investigations have shown good and promising results in studying the joint behaviour, there is clearly the potential to apply similar FE studies to other joint parameters.

Despite the demonstrated potential for using numerical analysis to study the effect of several parameters on the joint behaviour, there are several important aspects of the mechanical response of the joint that remains to be fully investigated. Friction plays a major role in bolted joints and even though some investigations have been conducted [44], the influence of the coefficient of friction between the plates on the joint behaviour is still to be fully understood. A few researchers [45-49] have investigated the effect of the bolt clamping force. Schön et al. [50-51] performed experimental studies measuring the coefficients of friction between several materials used as plates in composite bolted joints. They observed a wide variability in the coefficient of friction depending on the materials in contact, surface ply orientations and the wear of the surfaces caused by cyclic movements. This variability leads to changes in the maximum load transferred by friction using different plate materials or layups or, with the same joint, during its in-service life. This has a strong impact on the behaviour and strength of a joint. A numerical study could significantly contribute to an understanding of how the coefficient of friction influences the joint behaviour.

Despite the improvements in the numerical analysis of composite bolted joints during recent years, the level of detail implemented in FE models found in the literature is still not high enough to fully capture the global and local behaviour of the joints and the stress state in their critical locations. In order to have more reliable and accurate results, finer geometrical details, accurate modelling of the lay-ups, finer meshes, and an accurate definition of the contacts, are needed. In addition, all the referenced research has focussed on the behaviour of the composite plates while neglecting to model the bolts properly and, therefore, their effect on the joint mechanical response. In most of the previously published research the joints have

been studied in a condition of insignificant bolt pre-load but this case is far from representative of the range of working conditions of composite bolted joints in aviation. For this reason a model able to fully simulate bolt clamping and friction is needed. A few studies have been published on the effect of the clearance but a comprehensive and detailed investigation of the interaction between bolt clamping force, coefficient of friction and clearance and their effect on the joint behaviour is still required.

1.2.3. Analysis of the stress distribution around the holes of composite bolted joints under static loading

In the past, a significant number of experimental investigations have been published regarding the different failure modes of composite bolted joints under tensile loading. Several research groups [6-8, 52-53] studied the link between the geometrical relationships in the joints, such as w/d , e/d (Figure 1-1), and the type of failure modes occurring in the joints. It has been found that a sufficiently low w/d ratio (limited plate width) leads to a net-section failure, while a sufficiently low e/d (limited distance between a bolt and the plate run-out) leads to a shear-out failure. If none of these failure modes occur, and in absence of fastener failure, bearing failure becomes the dominant failure mode. Bearing failure is, due to its high energy absorption and high deformation before failure, the most desirable of the joint failure modes.

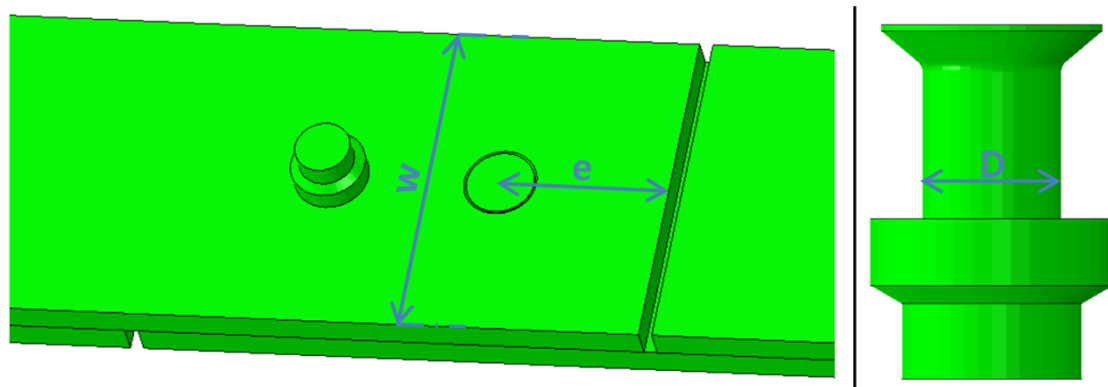


Figure 1-1. Main geometrical relationships in a single-lap bolted joint.

The damage micro-mechanisms for the bearing failure have been studied experimentally [54-57] analysing the damage in the joint section along the bearing plane, corresponding to different load levels applied to the joint. It has been found that bearing damage behaves as an accumulation of different types of damage, starting with matrix shear cracks which lead to compressive fibre failure and kinking in the 0° oriented plies and subsequently developing delamination and through-the-thickness shear cracks. The presence of lateral constraints, such as bolt heads and nuts, and of the clamping force, limit the formation of through-the-thickness shear cracks, forcing the damage to develop mainly through delamination [55]. In addition, it has been shown that the stacking sequence can influence greatly both the strength and the final failure mode occurring in the joints [8, 58].

Only a few works in the past have focused on the analysis of the stress state around the holes of bolted joints using the finite element (FE) method. Ireman [16] analysed the contact pressure distribution around the hole of single-bolt, single-lap hybrid (composite-aluminium) bolted joints with either a protruded or a countersunk bolt. Since the material properties in the composite plates were homogenised, it was not possible to back-calculate the stress state of the single plies. McCarthy et al. [59-60] investigated the tangential and radial stress distribution around the hole of a single-lap single-bolt composite bolted joint with either a protruded or countersunk

bolt. The results were obtained for cases of homogenised and non-homogenised material properties and focused on investigating the effect of the clearance on the stress distribution.

The works mentioned [16, 59-60] established the importance of the analysis of the stress distribution around the holes of composite bolted joints, thus motivating further investigation on the topic. In particular, an analysis of the stress from a ply perspective (stress components defined according to the material coordinate system), rather than from a hole perspective (tangential and radial stresses), is still missing. The analysis of the stress components in each ply, around the holes, allows the study of the relationship between the ply failure modes and the joint failure modes. Along with the stacking sequence of the plates, several joint parameters play an important role in determining the stress state and the strength of the joint. The occurrences of shear-out and net-section failures are greatly dependant on the e/d and w/d ratios and on the stacking sequence. While a 0° dominated plate is prone to shear out, a 90° dominated plate is likely to lead to a net-section failure. If this geometrical ratios are high enough, bearing failure is mainly influenced by the stress state of the material around the holes and by the bolt-hole contact. Some of the geometric parameters which could influence significantly the bearing strength are the bolt-hole clearance, the head height (in case of countersunk bolts) and the position of the bolts in the plates. While the effect of the clearance has been already analysed [60, 34-36, 38], the effects of the height of the countersunk head and of the position of the bolts in the plates are still to be fully explored.

1.2.4. Clamping force measurement

Bolt clamping force has a great importance on the behaviour and strength of bolted joints and safety of structures such as aircraft. A considerable amount of joint failures are caused by a wrong clamping force introduced during installation or by an excessive clamping force loss during service. There is no direct way to measure bolt

clamping force and, even though several indirect methods have been developed, this matter still proves to be challenging. In addition to this, the relation between clamping force loss, time and temperature has previously been highlighted [61] but the relation between clamping force loss and fatigue cycles is still to be investigated.

The most widely used way to measure bolt clamping force is using a torque wrench. Even though this method is easy to implement, it has been proven to be very imprecise since it relies on an estimation of the coefficient of friction between nut, plate and bolt. A more sophisticated method uses strain gauges; these can be applied on either a bush located between nuts and plate [62] or directly embedded internally to the bolts [63-64]. This method has shown to be precise but needs a specific specimen setup (such as holes in bolts or additional bushes), which, in most of the cases, could modify the strength and behaviour of the specimen. More advanced methods involve the use of ultrasonic waves to acquire the length or the tension of bolts [65-66]. Even though the use of ultrasonic waves has shown promising capabilities to measure bolt clamping forces, the possible need of special specimen setup and the dependence of the readings on the bolt head and nut shape still limit its industrial application. More recent methodologies involve the use of interferometers [67] and digital image correlation techniques [68] to detect either the out-of-plane displacements or the strain of the plates. These methodologies do not require any modification to the specimen but, on the other hand, need to have a complex setup and have strict limitations on the type of specimen and test configurations that can be studied. Even though each of the methods mentioned has proven to work successfully for specific tests or applications, there is still the need for a new methodology developed to monitor the clamping force of bolted joints continuously during fatigue tests and without modifications to the specimens.

1.2.5. Joint fatigue mechanical behaviour

A few researchers have investigated the effect of some important joint parameters on the fatigue performances of composite bolted joints. Several researchers [69-74] have highlighted the beneficial effect of the clamping force on the joint fatigue life. Higher clamping forces increase the friction between the plates, therefore reducing the load transferred through bearing. Few researchers [69, 75-76] highlighted the positive effect of higher plate thicknesses on the joint static and fatigue performances. Starikov et al. [77-78] and Persson et al. [71] investigated the effect of the number and disposition of bolts and found a linear dependency between number of bolts installed and fatigue performances. Lim et al. [70] investigated the influence of the stacking sequence in fatigue. Starikov et al. [79] investigated also the impact of the load conditions on the joint fatigue performances, running fatigue tests at different R ratios without changing the joint configuration, and indentifying $R = -1$ as the worst load condition. Other researchers [54, 78, 80-81] have, instead, studied the evolution of the fatigue bearing damage and highlighted a bearing failure micro-mechanism similar to what observed in static testing. In both cases the fibre kinking of the 0° oriented plies acts as trigger of the failure process. All the cited works regarding joint parameters focus on the fatigue life length of the joint (cycles to fatigue failure) but none of them investigated the complex joint mechanical behaviour during the fatigue test and how this is influenced by the studied parameters. In addition, a similarity between the bearing damage evolution in static and fatigue testing has been observed. This motivates a further comparison between the static and fatigue joint mechanical behaviour, with the aim of finding a possible correlation between them and, subsequently, reduce the number of fatigue tests needed to characterise a joint configuration and improve the joint design in every load condition.

1.3. Aims and objectives

The overall aim of this thesis is to improve our understanding of the mechanical behaviour of single-lap composite joints with countersunk bolts. The detailed objectives are:

- To develop a finite element (FE) model to simulate and investigate in detail the mechanical behaviour of two-bolt single-lap composite joints with countersunk bolts under static loading.
- To investigate the stress distributions around the holes of composite bolted joints under static loading, linking them to the ply failures and joint failure modes.
- To investigate experimentally the mechanical behaviour of composite bolted joints under fatigue loading, monitoring the loss of bolt clamping force during the cycles.

1.4. Structure of the thesis

To pursue the described objectives, a series of researches have been conducted. These are described in the chapters of this thesis, each addressing a specific objective. The thesis is composed of:

- Chapter 1. This chapter presents a detailed parametric FE model of a two-bolt, single-lap composite bolted joint, with countersunk fasteners, under static tensile load. The static joint behaviour is analysed and parametric studies are run to investigate the effects of clamping force, coefficient of friction and clearance. The evolution of the contact between the bolts and the holes is

investigated and the numerical results are compared with experimental data.

Chapter 2. This chapter presents a FE analysis of the stress distribution around the holes of single-lap composite bolted joints, with two countersunk bolts, under tensile loading. The distribution of the six stress components around the holes (defined according to the material coordinate system) is obtained and discussed. Joints with different countersunk head height, bolt-hole clearance and bolt position are analysed to study the effects of these parameters on the stress distribution. As a result, a relation between the stress distributions, the ply failures and the joint failure modes is presented.

Chapter 3. This chapter presents fatigue experimental tests on composite bolted joints with the use of a novel method to monitor in real-time the loss of clamping force and detect crack initiation and propagation in the countersunk fasteners, using strain gauges and an algorithm to process the data. The method is validated and the experimental results are obtained, testing joints with different thicknesses and countersunk bolt heads, are discussed. The variation of the clamping force during the fatigue test is investigated, as well as the interaction between the bolts during the failure process. A connection between static and fatigue test results is highlighted. As outcome of the investigation a joint fatigue failure sequence is presented.

Chapter 4. This chapter summarises the conclusions drawn in the thesis.

Chapter 5. This chapter suggests some actions to expand the work presented in this thesis and continue increasing the understanding of the mechanical behaviour of composite bolted joints.

Chapter 2

A detailed finite element investigation of composite bolted joints with countersunk fasteners

2.1. Introduction

The mechanical response of composite bolted joints can be complex due to the interaction between the several joint parts, the inherent complexity of composite materials and the various parameters which can influence the joint behaviour (such as coefficient of friction, preload and clearance). This can be studied with a large amount of experimental tests, which could be both time consuming and very expensive, or, more efficiently, by the integration of selected experimental tests and a sufficiently detailed and flexible finite element model.

This chapter presents a very detailed parametric FEM model of a single lap shear composite bolted joint (Figure 2-1), with countersunk fasteners, under static tensile load. The stress states of the CFRP plates and bolts are discussed, the evolution

of the contact between the bolts and the holes is analysed and the numerical results are compared against experimental data. Five stages have been identified in the joint behaviour and parametric studies are presented showing the effects of clamping force, coefficient of friction and clearance on these stages.

2.2. Numerical model

The developed 3D finite element model of a single lap composite bolted joint (Figure 2-1) has been produced with Abaqus 6.10 [82] using a non-linear geometric dynamic implicit formulation. The specimen, as well as the model, is composed of the following parts (Figure 2-2):

- 2 countersunk fasteners composed of anodised titanium (Ti-6Al-4V) bolts and steel nuts (shank diameter of 6.35 mm and countersunk angle of 100 degrees);
- 2 main plates made of unidirectional carbon fibre reinforced plastic (CFRP) T800/M21 plies with a quasi-isotropic stacking sequence ([(+45, -45, 0, 90, -45, +45, 0, 90)₂]_s for a total plate thickness of 5.888 mm) ;
- 2 CFRP support plates adhesively bonded to the main ones in order to avoid excessive bending. Material and stacking sequence equal to the main plates.

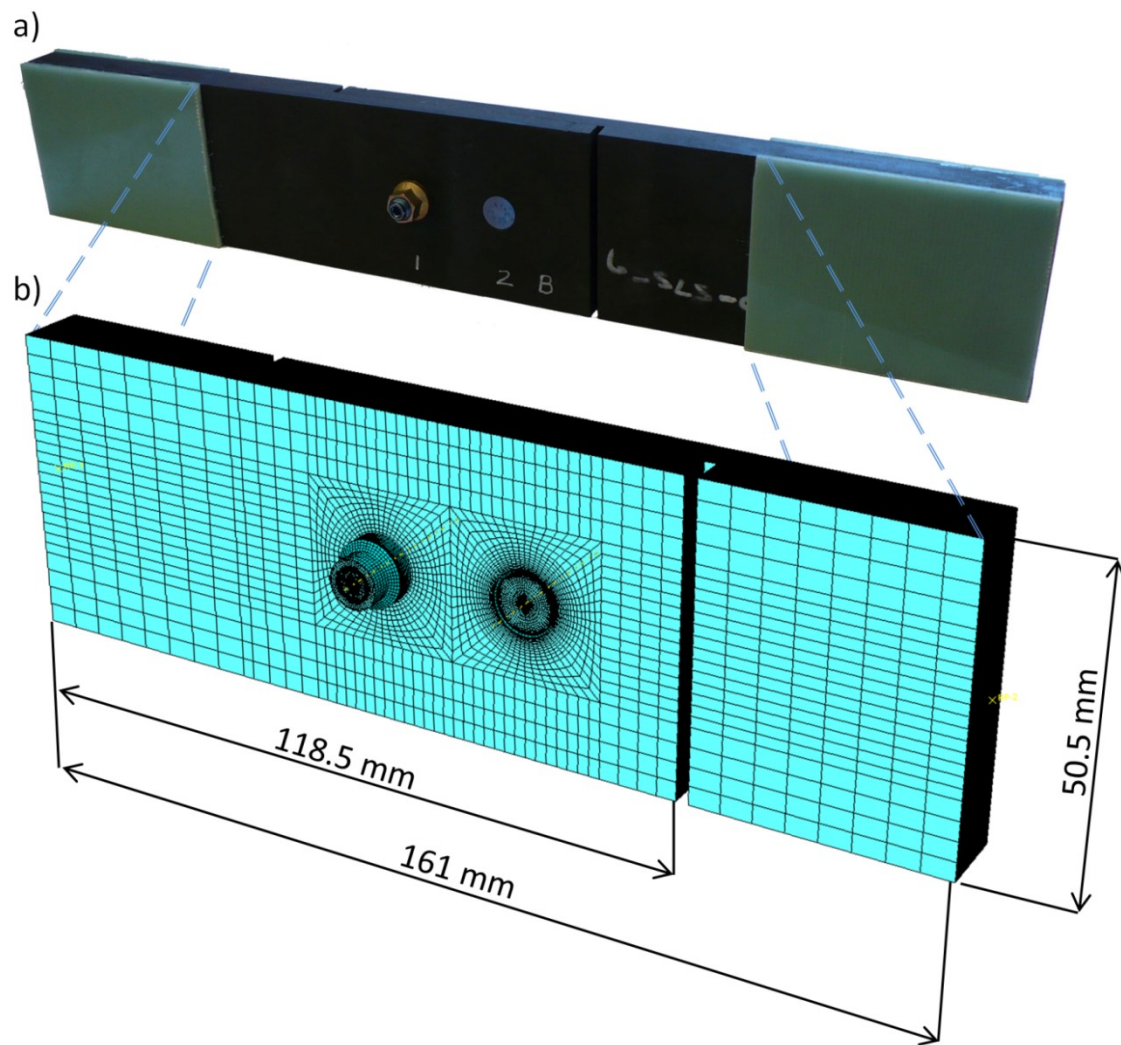


Figure 2-1. (a) Specimen of a composite bolted joint for the experimental unsupported single-lap shear test. (b) Finite element model of a composite bolted joint.

The model represents the portion of specimen (Figure 2-1) between the two pairs of jaws in the experimental test. Assuming a perfect clamping of the specimen, at each end of the model the jaws and the gripped portion of the specimen (end tabs) are modelled as a rigid body. One of these two rigid bodies has all degrees of freedom suppressed (including rotations), simulating the fixed jaws, while the other is free to move only along the longitudinal direction of the specimen, representing the moving jaws. The bonding between main and support plates is modelled using tie constraints.

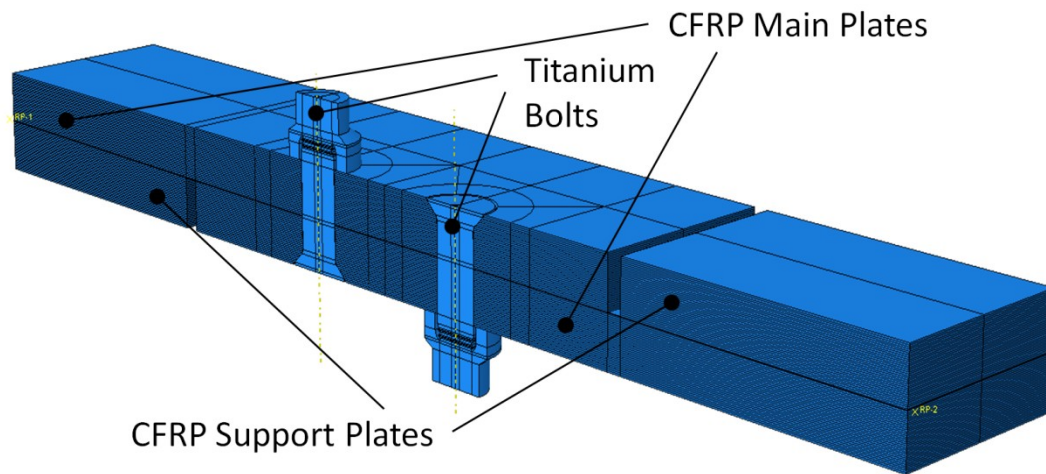


Figure 2-2. Section of the FE joint model with indications of the joint parts and visualization of the geometrical partitions of the parts.

The model is completely parameterised to easily study the effects of several parameters on the results, while its geometry and mesh are sufficiently detailed to replicate the key features of bolts and plates. The geometrical data of bolts and countersink are taken from their datasheets or directly measured from the actual specimens before the tests. In the bolts the transition between head and shank is accurately modelled by introducing the fillet between the two zones (Figure 2-3). The rounded transitions between countersinks and the straight portions of the holes are also represented and the axis of the bolts and corresponding plate holes are taken to be coincident. The clearance between the bolt shanks and the plate holes is included. In the bolts, the part of the thread not in contact with the nut is modelled as an axial revolution of the actual thread section; this allows for an accurate stress analysis of the area without excessively increasing the mesh complexity. Bolt and nut are modelled as a single part but using different materials, titanium and steel respectively, with the nut partition surrounding the bolt.

The elements used in the plates are first-order hexahedral elements (or brick elements), with a full-integration formulation employed around the holes, and a reduced-integration formulation used in the rest of plates. The bolt mesh comprises

reduced-integration first-order brick elements together with a cylindrical core of first-order wedge elements. Using a core of wedge elements allows the model to employ fewer elements at the centre of the bolts, where there are low stress gradients, and to have a more regular mesh. The mesh density used is increased at locations where high stress gradients are anticipated. These locations are close to the hole surfaces, close to the bolt cylindrical surfaces, at the head-shank transitions, in the shanks at the plane of the faying surface and at the threads.

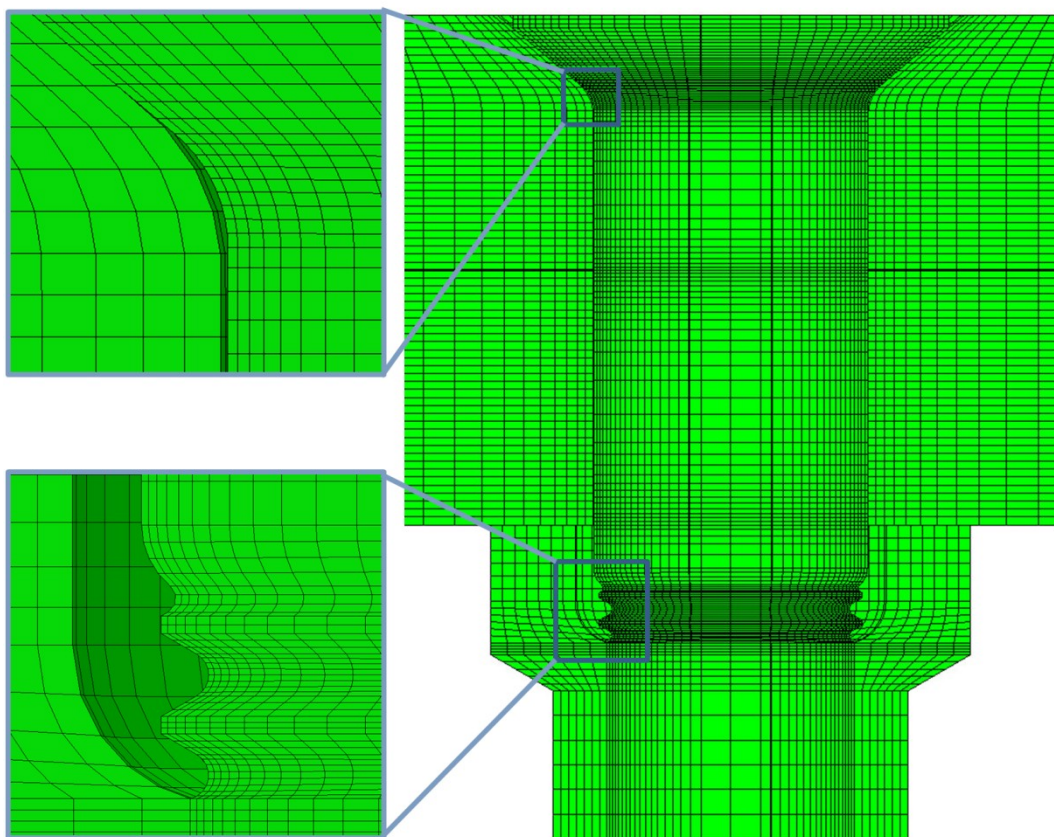


Figure 2-3. Details of the mesh in the section of a bolt and plates in the FE model (zoom on the head-shank transition, countersink-straight hole transition and bolt threads).

Two material definitions are used for metals: titanium has a bilinear elastic-plastic formulation while the steel is simply defined with a linear elastic law (There is no need to include plasticity in the nuts since stresses are lower than the steel yield

stress). The CFRP is modelled with a linear elastic law as an orthotropic material and defining the orientation for each ply. In order to have a good representation of the stress-strain field in every point of the laminate, one element is used for each ply through the thickness.

A full definition of the contact zones is implemented. Contact is modelled between (i) the main plates, (ii) between bolts (heads and shanks) and plate holes and (iii) between plates and nuts (Figure 2-4). The contacts are solved using the penalty method with hard contact, friction and finite sliding. A node-to-surface discretisation is used for the contact between the plates while a surface-to-surface discretisation is employed for the contacts between bolts and plates to avoid element interpenetrations at the edges of the parts. Two different coefficients of friction are used in the model, depending on whether the contact is between composites and composites or between composites and metal.

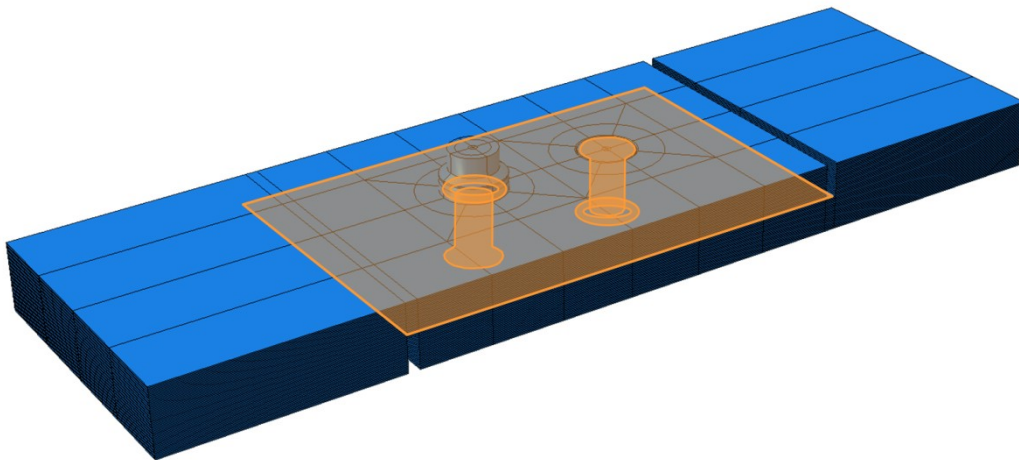


Figure 2-4. Contact pairs in the FE model.

The analysis is divided into two steps:

1. The clamping force is applied to the bolts. A selected layer of elements in the bolt is progressively shrunk along the bolt axis until the sum of the reaction forces in the layer is equal to the desired clamping force. This is

implemented using the 'Bolt Load' command [82]. This step simulates the assembly of the joint.

2. A longitudinal displacement is applied to the rigid body representing the moving jaws. This step simulates the experimental displacement-controlled static test.

2.3. Results

2.3.1. Result Overview

Several FE analyses have been run using the model described in the previous section. The first aim of these simulations is to study the mechanical response of the joint as the clamping force is applied and, in addition, as the longitudinal displacement is imposed to the joint. The second aim is to investigate the joint behaviour analysing in detail the interaction between the joint parts and comparing the results with experimental data. The third is to study the change in the joint behaviour when varying:

- the clamping force applied to the bolts;
- the coefficient of friction between the composite plates;
- the clearance between bolts and holes.

The analysis results are compared with experimental data from unsupported single-lap shear experimental tests, carried out in parallel with the numerical work. The specimens used had the same dimensions and features as the FE model. The key parameters used in the model for the study of the mechanical response, joint behaviour and for the comparison with experimental data are:

- Clamping force applied to each bolt : 10,000 N (experimentally found to correspond to 7.35 Nm);

- Coefficient of friction between composite plates : 0.324.
- Coefficient of friction between composite plates and bolts : 0.16.
- Clearance (difference between hole and bolt diameter) : 0.06 mm.

2.3.2. Mechanical response

After the clamping force is applied to the bolts in the model, the bolt head is partially sunk in the countersink hole while the plates are bent in a convex shape around heads and nuts. In Figure 2-5, it is possible to observe the development of von Mises stress concentrations at the head-shank transition and at the first thread from the nut. In addition, it has been found that the 10.000 N clamping force is high enough to cause the formation of plastic strain at those locations. Thus a limited amount of plasticity is developed in the bolts even before the longitudinal displacement is imposed.

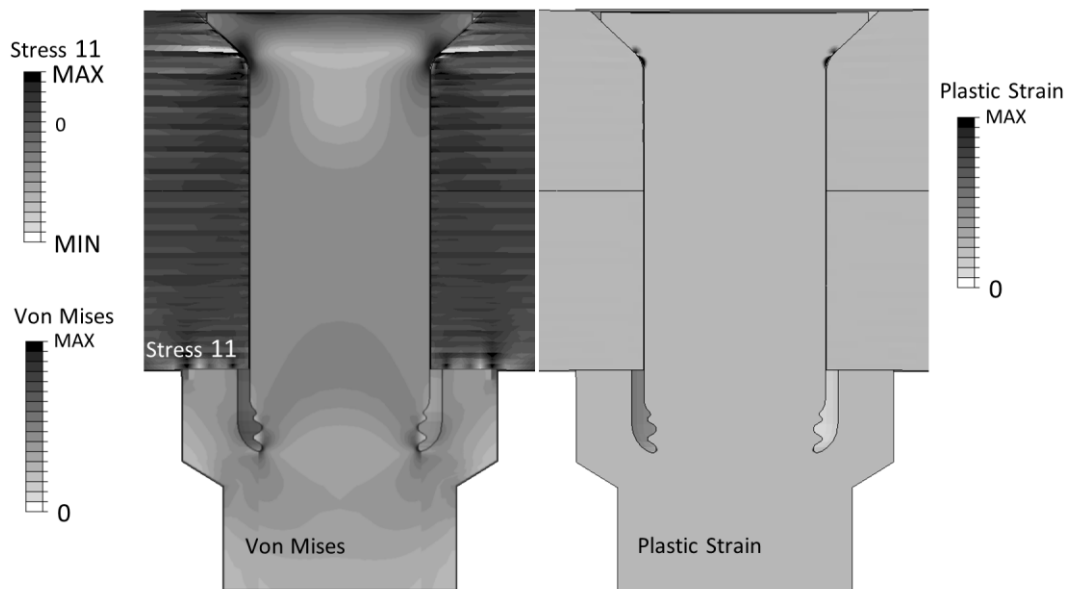


Figure 2-5. σ_1 , Von Mises stress and plastic strain in the bolt section after having applied the clamping force.

As the longitudinal displacement is imposed to the specimen, the model shows a secondary bending along its length and a progressive separation of the plates (Figure 2-6). Analysing the model section (Figure 2-7), fastener bending inside the plates can be noticed. The relative movement of the plates leads to the contact between the bolt and two sides of the holes: at one side of the hole in the upper plate and the opposing side in the lower plate. Two locations with high concentrations of von Mises stress and plastic strain can be identified in the bolts. These correspond to the head-shank transition and to the first thread from the nut. In the experimental tests used for the validation, these are found to be the locations where the cracks develop leading to the joint final failure. In line with the faying surface, high shear stress and plastic strain are found in the shanks while a high stress state is predicted in the composite plates at the internal hole edges. Experimental results support this since residual bending of the bolts in the shank and localised bearing damage at the edges of the holes can be observed.

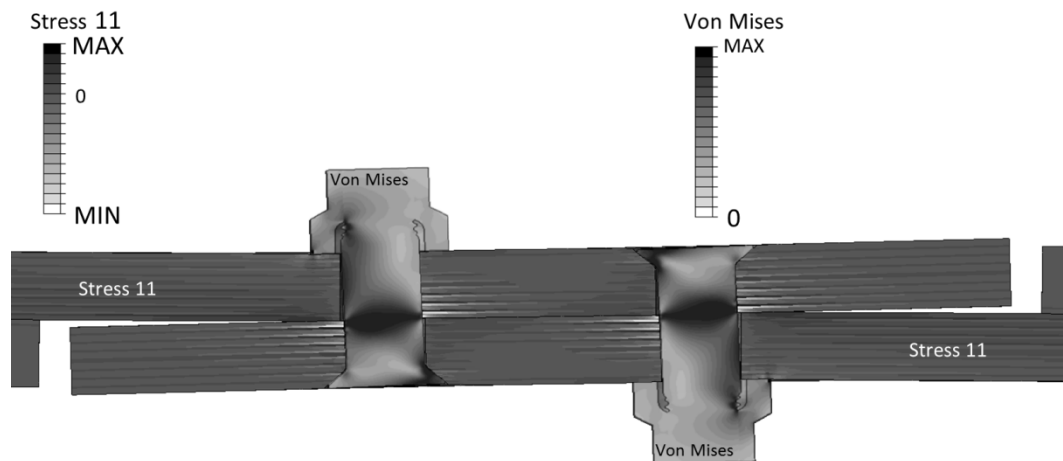


Figure 2-6. Secondary bending in the model section when the external load is applied (σ_1 and von Mises stress as contour).

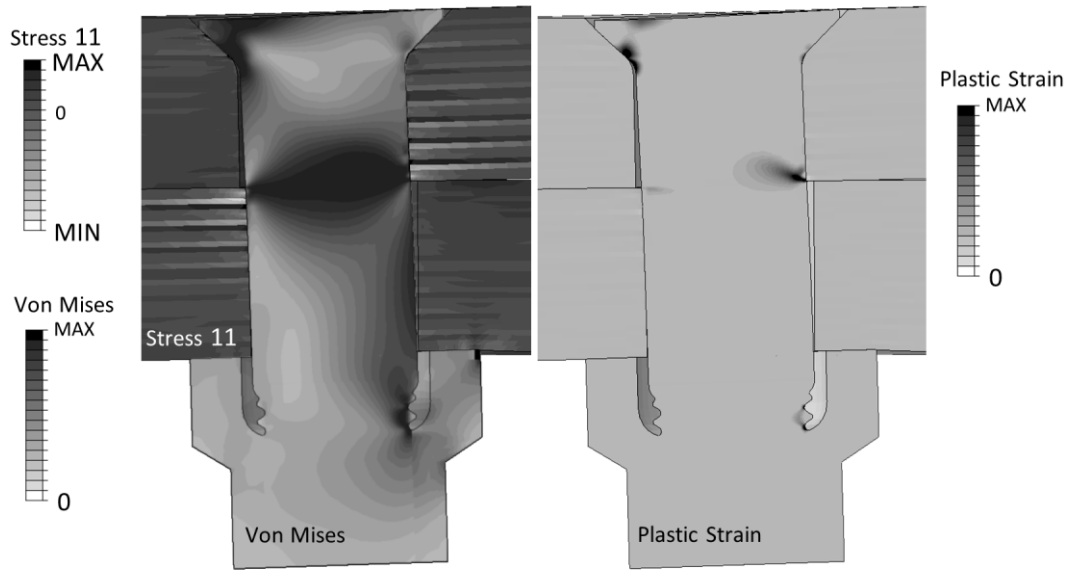


Figure 2-7. σ_1 , Von Mises stress and plastic strain in the bolt section when the external load is applied.

2.3.3. Joint behaviour and comparison with experimental Data

Figure 2-8 shows the load-displacement curve obtained from the numerical model and the corresponding contact status between the bolt and plates at significant points of the curve. The simulation includes an unloading-reloading phase to study the joint behaviour in this scenario.

Figure 2-8 shows that the load-displacement curve predicted by the FE model exhibits a series of features: these are a short initial linear phase of high stiffness followed by a softening phase, a large phase of linear response and a final softening phase. The unloading-reloading phase appears as a loop with the initial and final points almost coincident. Figure 2-8 shows the correlation between these phases and the evolution of the contact between bolt and plates:

1. Initial point. The clamping force is applied to the bolt, the two portions of the hole are aligned and the bolt and the plates are in contact only through the head and the nut.
2. End of the first linear phase. There is still no relative movement between the plates.
3. Relative movement between the plates, still no contact between bolt shank and holes and joint stiffness greatly reduced.
4. First contact between the bolt shank and the plate with the straight hole, joint stiffness increased.
5. First contact between the bolt shank and the plate with the countersink. Larger contact surface between shank and straight hole. Joint stiffness increased and reaching the value of the second linear phase.
6. Large relative displacement between the plates, large fastener bending and extended surfaces in contact between the bolt and plates. All the surfaces in contact are slipping.
7. Middle point in the unloading path. Limited movements between the plates, extent of contact surfaces very similar to the previous point but with almost total sticking in the contact. Higher joint stiffness than at the previous point.
8. End of the unloading path. Contact surfaces similar to the point before the unloading path (point 6) but with the introduction of slipping respect the previous point (Point 7).
9. Middle point of the reloading path. Contact surfaces similar to point 6 but with extensive sticking.
10. Point after the loop. Contact status, fastener bending and plate relative displacement almost identical to what seen immediately before the unloading-reloading path (point 6).

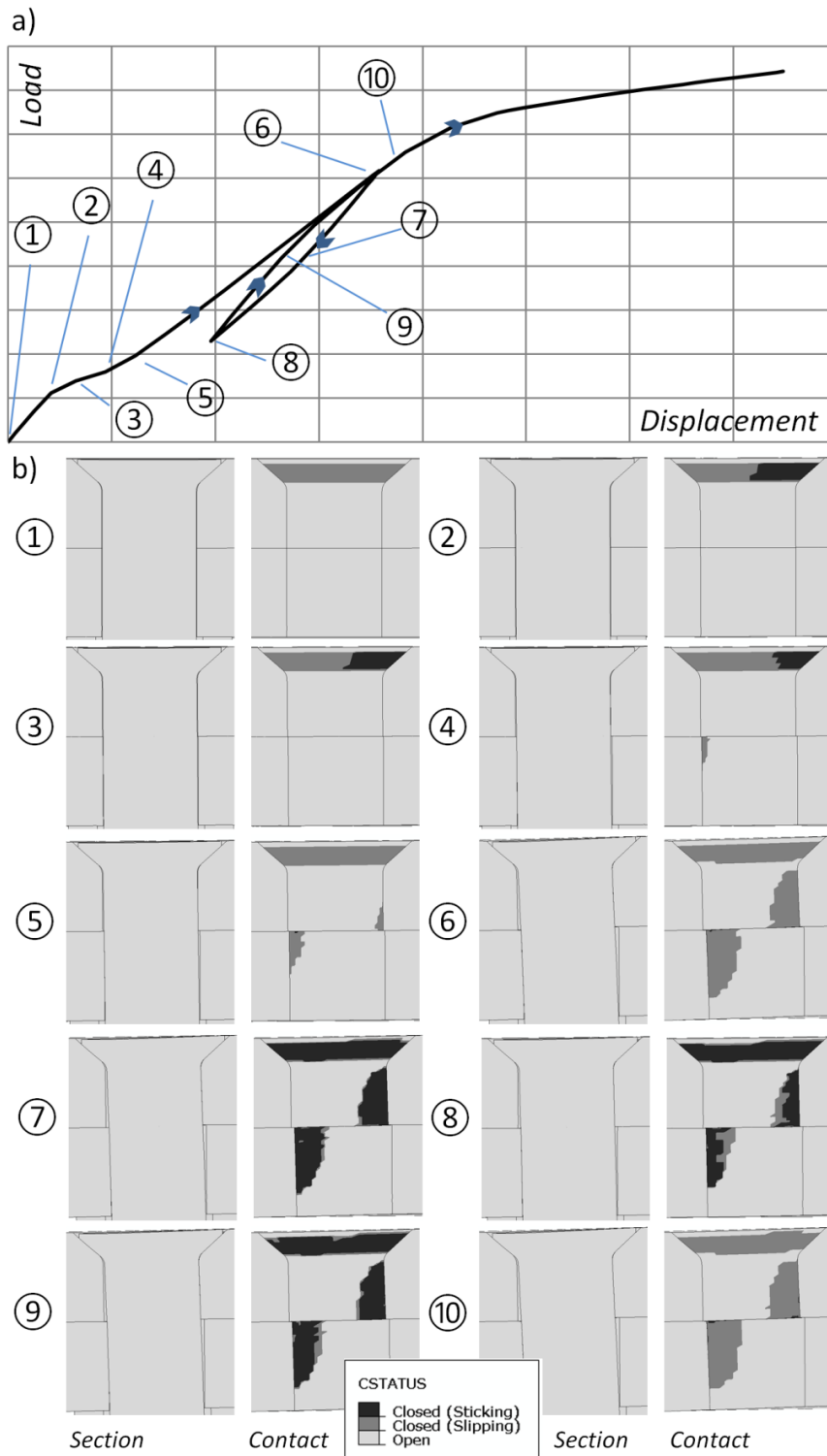


Figure 2-8. (a) Load-displacement curve of the joint obtained from the FE model; (b) Analysis of the bolt-holes interaction (deformations of the parts in the section and contact status) in significant points of the curve.

Figure 2-9 illustrates the good agreement between numerical and experimental results and shows that the load-displacement response predicted by the FE model exhibits the same features as the experimental data, including the unloading-reloading loop. The displacement in the experimental tests is taken through LVDTs, as described in ASTM D5961/D5961M [3], while in the numerical model is defined as the distance between the two reference points. In the experimental tests the final softening phase, which ends with a sudden drop in load as the joint fails, includes bearing damage while in the model only bolt plasticity is contributing to the predicted softening of the phase. To improve the prediction of the final phase, a bearing damage model should be developed.

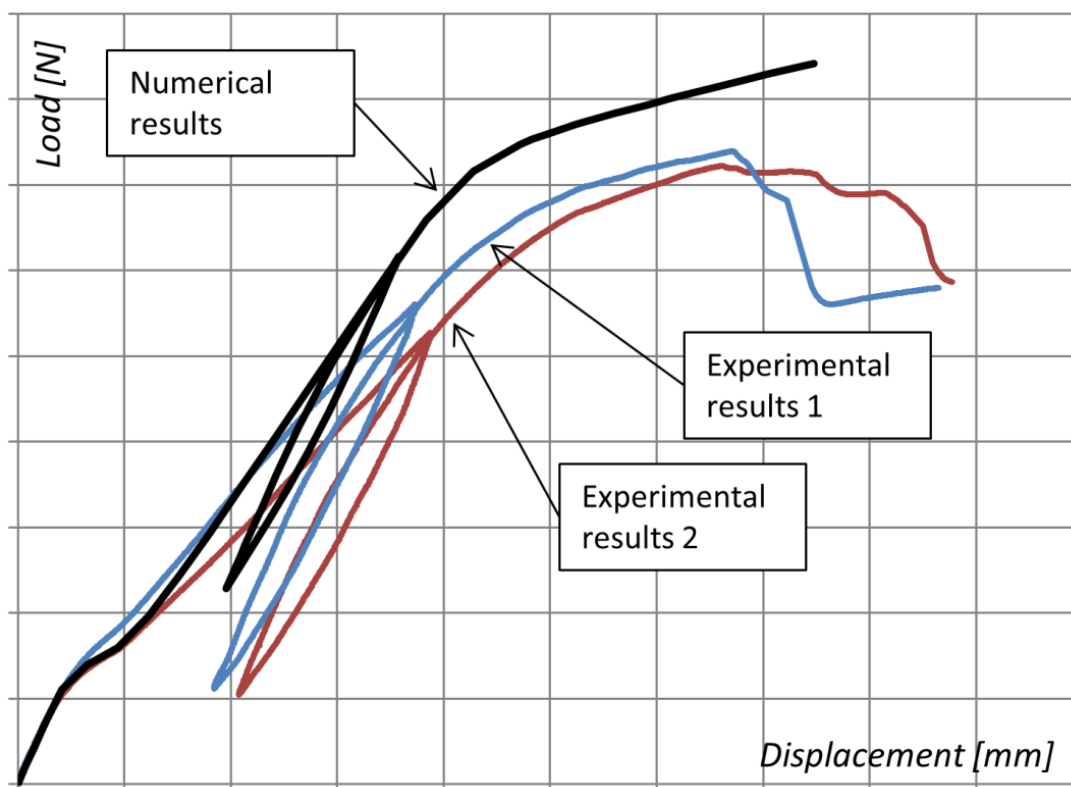


Figure 2-9. Comparison between numerical and experimental load-displacement curves of the joint (including the unloading-reloading loop).

2.4. Parametric studies

Three parametric studies have been run using the previous model as a base but varying a single parameter each time to investigate its effect on the joint behaviour. The unloading-reloading loop has not been included in the parametric studies but this could be subject of investigation in future work.

The first parametric study has been run varying the coefficient of friction between the plates in order to study its effect on the joint behaviour. The coefficients of friction used are 0.03, 0.15, 0.324, 0.45 and 0.6. As can be seen from Figure 2-10, having a higher coefficient of friction leads to a longer first phase of the behaviour, characterised by a higher stiffness, and to a general higher curve on the load-displacement graph.

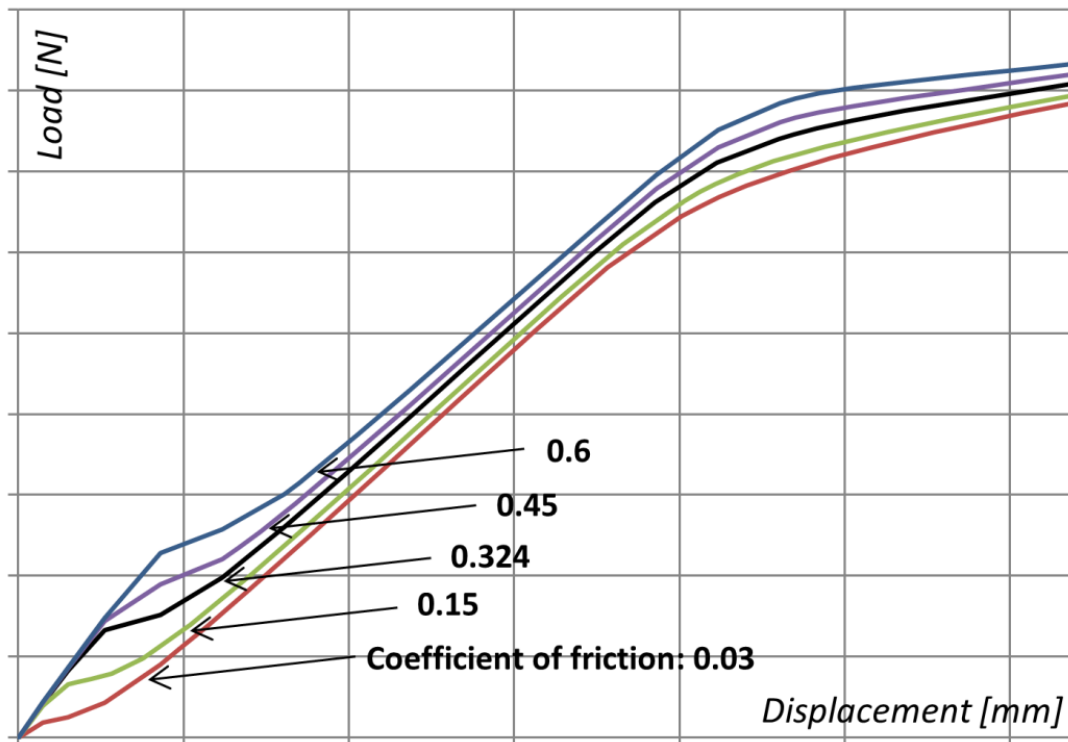


Figure 2-10. Parametric study of the effect of the coefficient of friction on the joint behavior.

The second parametric study investigates the effect of the clamping force on the joint behaviour. The clamping forces used are 1, 5000, 10000, 12000 and 15000 N. Figure 2-11 shows a longer first stage of the behaviour, which is similar to what seen studying the coefficient of friction, but limited differences to higher applied loads.

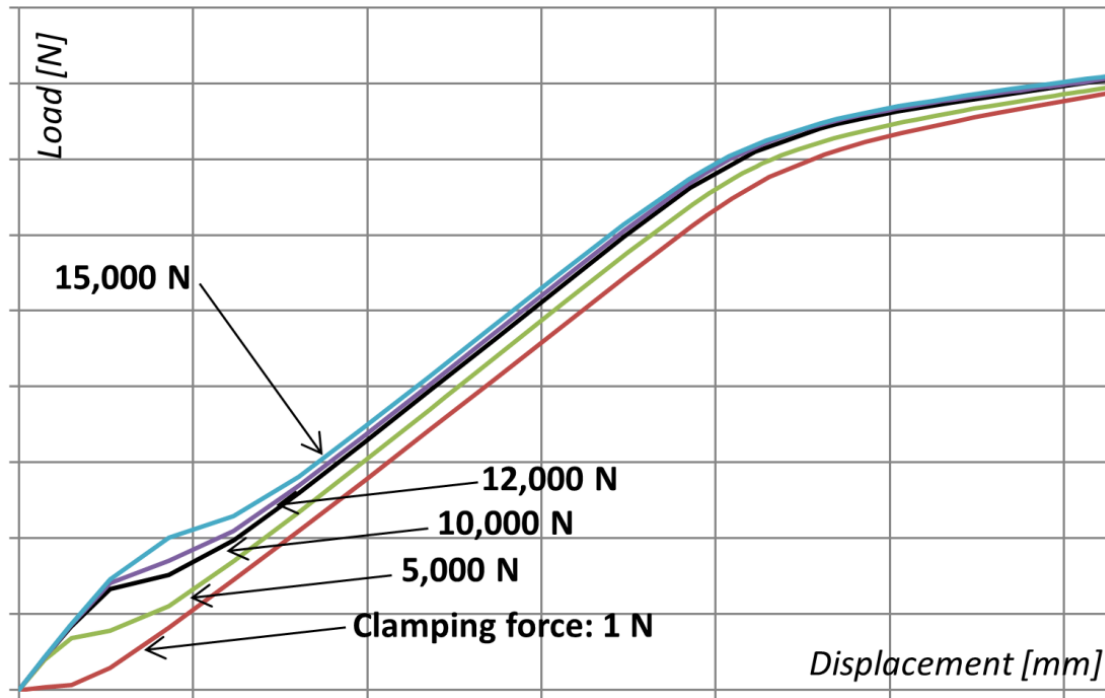


Figure 2-11. Parametric study of the effect of the clamping force on the joint behavior.

The third parametric study focuses on the effect of the clearance on the joint behaviour. The clearances investigated are 0, 0.03, 0.06, 0.12 and 0.3 mm. As shown in Figure 2-12, increasing the clearance does not modify the first high-stiffness stage but it has the effect of delaying the start of the second stiff stage of the behaviour.

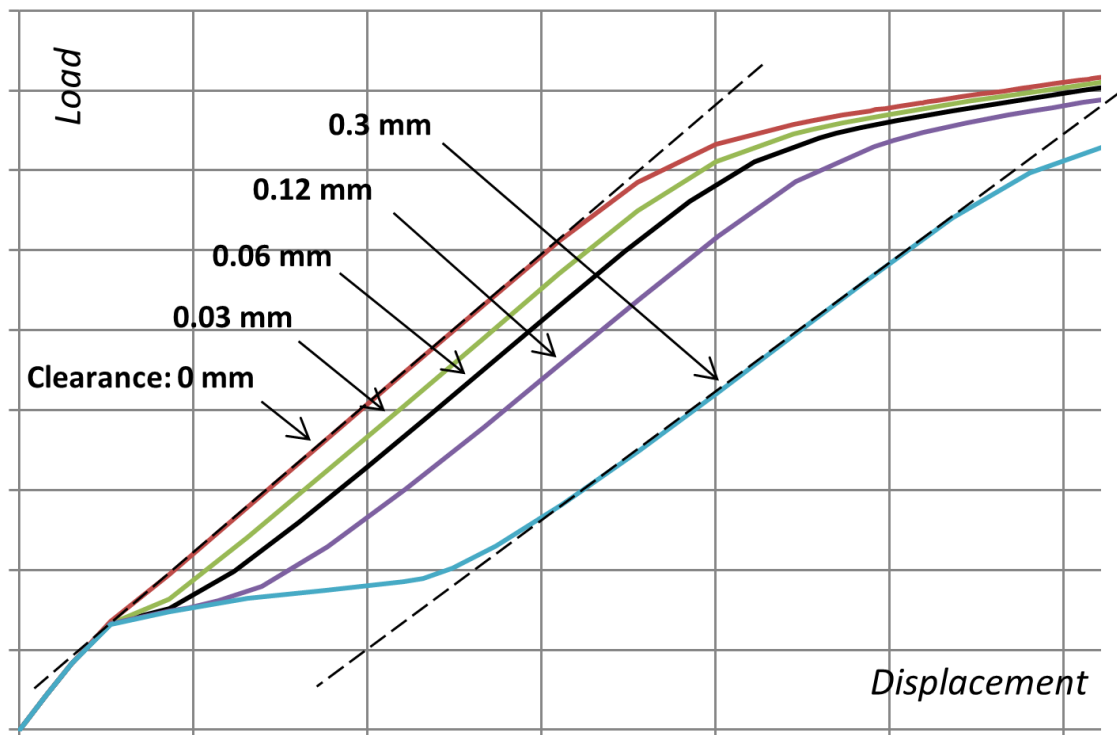


Figure 2-12. Parametric study of the effect of the clearance on the joint behavior.

2.5. Discussion

2.5.1. Five stages in the joint behaviour

From the numerical and experimental data presented in the previous section, it is possible to identify five stages in the joint behaviour (Figure 2-13):

1. No-Slip
2. Slip
3. Full Contact
4. Damage
5. Final Failure

The *No-Slip* stage has the highest stiffness of all five stages and the numerical model shows that this stage is characterised by the absence of relative movement between the plates in the contact and so the load is almost totally transferred by friction. The maximum load that can be transferred only by friction has been found to be approximately the product of the clamping force applied, the coefficient of friction and the number of bolts. As seen from the parametric studies in the previous section, the stiffness of the *No-Slip* stage does not change when varying coefficient of friction, clamping force or even clearance. Thus it can be concluded that the stiffness of this joint in the *No-Slip* stage depends essentially on the stiffness of the plates.

The *Slip* stage starts when the maximum load transferable only by friction is exceeded. From that point the plates start to slip and close the clearance between bolts and holes without the need of a significant increase of the load applied. This is in agreement with what was found by McCarthy et al. experimentally [40] and numerically [42] in the case of a single-lap single-bolt joint with no preload. Because of the different diameters of bolts and holes and the distortions of the joint parts by secondary and fastener bending, the first contact between bolt and hole edges is on a very limited surface. First the contact occurs between the shank and the plate with the straight hole and subsequently between the shank and the plate with the countersink. This is due to the fact that, in the plate with the countersink, part of the load is transferred through the countersunk head. This results in a stiffer connection than the one between the nut and the plate with the straight hole and to a delayed contact and slightly higher load required to achieve the contact. Figure 2-8 shows that when the bolt shank comes in contact, first with the straight hole, and then with the countersink hole, the joint stiffness is increased. This has the effect of creating a smooth transition to the full contact stage (Figure 2-8). The length of this transition appears to be proportional to the amount of clearance in the joint (Figure 2-12). The applied displacement change during the *Slip* stage is approximately equal to the amount of clearance, which is the difference between the diameters of bolts and holes, plus the length of the transition zone. It should be noted that, even if a nominal clearance of 0

mm is chosen, the joint may still have some limited clearance due to the effect of the clamping force enlarging the plate holes. From the parametric studies presented in the previous section, stiffness and length of the *Slip* stage are not affected by the change of coefficient of friction or clamping force.

The *Full Contact* stage is characterised by the majority of the load being transferred by the contact between bolt shanks and hole edges. The stiffness of this stage is lower than the one of the *No-slip* stage due to the local compliance of the contact between bolt shanks and hole edges. The presented parametric study shows that an increasing clearance leads to a lower stiffness in the *Full Contact* stage of the behaviour (Figure 2-12). This is because a higher clearance implies more different diameters between bolt shanks and holes resulting in more mismatching surfaces in contact, more significant fastener bending, and, thus, a smaller area in contact. A similar loss in stiffness has been found by Mc.Carthy et al. [40, 42] in the case of a single-lap single-bolt joint with no preload. The numerical study shows that the joint stiffness in the *Full Contact* Stage is unaffected by the bolt clamping force and the friction coefficient between the plates.

The *Damage* stage is characterised by a steady reduction in stiffness. In the numerical model this stage is driven by the development of shear plastic strain in the bolt shank at the faying surface but in the experiments the damage also includes bearing damage which is not represented in the current model.

The final failure of the tested joints, in the *Final Failure* stage, resulted from cracks growing from the head-shank transitions and the first threads. This led to a sudden drop in the load carried by the joint. There may be other failure modes, such as pull-through of the bolts, excessive bearing damage, net-section failure or shear-out depending on the bolt and plate geometry and properties.

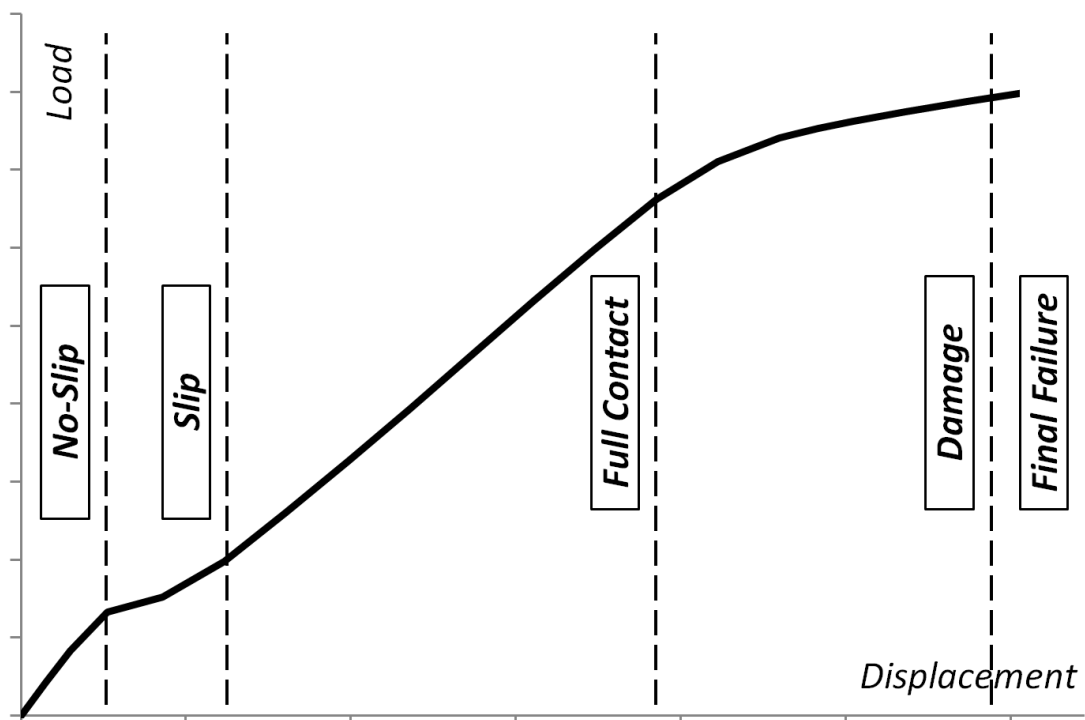


Figure 2-13. Five stages identified in the joint behavior.

2.5.2. Unloading - reloading loop

The unloading-reloading loop shown in Figure 2-8 and Figure 2-9 is characterised by a higher joint stiffness than that seen in the *Full Contact* stage. This different joint stiffness is likely to be caused by a combination of several phenomena such as limited relative movements between the plates, plate unloading and sticking of the bolts in the holes. As can be seen in Figure 2-8 the relative movements between the plates are limited during the loop and the slipping between bolts and hole is small. This is due to the friction between the plates opposing to the relative movements (in the reloading path in the opposite direction as before) and reacting to the elastic forces of bolts and holes. Since there is limited movement between the plates, the joint is likely to be in a situation similar to the *No-Slip* stage and, therefore, with a high joint stiffness largely dependent on the plate stiffness.

From Figure 2-8 and Figure 2-9 it is possible to observe the different load paths during the unloading and reloading of the joint. This phenomenon is likely to be caused by the friction opposing the relative movements between the plates and between the bolts and the holes, first in one direction, then in the opposite. This leads to the creation of two different load paths and the dissipation of an amount of energy equal to the area included between the unloading and reloading path.

The joint behaviour in the unloading-reloading loop is far from being completely understood. Further investigations, such as parametric studies, are required to achieve a deeper understanding of the joint behaviour in this phase and could be subject of future work.

2.6. Conclusions

This chapter presents a very detailed FE model of a single lap shear composite bolted joint, with titanium countersunk bolts, under static tensile load. The model comprises a high level of geometrical details in the plates and bolts (such as the bolt threads and clearance), the simulation of the bolt preload and a complete contact definition.

The numerical results have a good agreement with the experimental load-displacement curves (including an unloading-reloading loop), especially in the first part of the test, and the model has been able to identify correctly the critical locations within the joints. The analysis of the contact status between bolt and plates, during the joint loading, has highlighted the correlation between the contact status and the joint stiffness.

Parametric studies of the effect of the coefficient of friction, clamping force and clearance on the joint behaviour have been run. According to what was found in these studies and in the experimental data, the joint behaviour can be divided in 5 stages: (i) *No-Slip*, (ii) *Slip*, (iii) *Full Contact*, (iv) *Damage* and (v), *Final Failure*. In the *No-Slip* stage

the load is transferred only by friction. The stiffness in this stage is the highest of all five stages and is found to depend only on the plate stiffness; the clamping force and coefficient of friction define the maximum load transmitted only by friction. The *Slip* stage occurs when the maximum load transferable by friction is exceeded, it is characterised by a very low stiffness and its length is defined by the amount of clearance. In the *Full Contact* stage most of the load is transferred through the contact between shanks and holes, the stiffness is lower than in the *No-Slip* stage due to the compliance of the contact. It has been found that increasing clearance leads to a lower stiffness in this stage due to a more limited contact area.

The presented model does not yet reproduce accurately the last part of the joint behaviour since damage in composites is currently not included. A bearing damage model is under development and it could be included in a future version of the model.

2.7. Publications

The work presented within this chapter has resulted in the following publication:

“C. Stocchi, P. Robinson, S.T. Pinho, A detailed finite element investigation of composite bolted joints with countersunk fasteners, Composites Part A: Applied Science and Manufacturing, Volume 52, September 2013, Pages 143-150”

Chapter 3

Stress distribution analysis around the holes of single-lap composite bolted joints under tensile loading

3.1. Introduction

The introduction of composite materials has allowed the development of more efficient structures in terms of stiffness, strength and weight. At the same time, the inherent complexity of composites demands a deeper understanding of the material's behaviour to design reliable and efficient structures. The stress state around the holes of a composite bolted joint can be extremely complex and may have a strong influence on the joint strength. To design better composite bolted joints it is of great importance to study the link between the failure mechanisms, the stress state around the holes and the joint design parameters.

This chapter presents a finite element analysis of the stress distribution around the holes of single-lap composite bolted joints, with two countersunk bolts, under

tensile loading. The distribution of the six stress components around the holes (defined accordingly to the material coordinate system) is obtained and discussed. Joints with different countersunk head height, bolt-hole clearance and bolt positions are analysed to study the effect of these parameters on the stress distribution. As a result, a relation between the stress distributions, the ply failures and the joint failure modes is presented.

3.2. Method

3.2.1. Finite element model

The proposed method uses the 3D FE model of a composite single-lap bolted joint, fully described in the previous chapter, to study the stress state of the composite material around the holes when the joint is loaded in tension. For a more exhaustive and detailed explanation of the FE model, refer to Chapter 2.

3.2.2. Stress analysis method

The stress field is extracted at the end of the second analysis step for each ply of the two main plates, in the first ring of elements around the holes. To obtain a single stress state for each element, the stresses at the centroid, interpolated from the 8 Gauss-point values, are used. In fact, any other point in the element could have been equally used to read the stresses without any discernible effect, since the mesh is very refined. The first ring of elements have been analysed, rather than elements further from the hole, to investigate the distribution of stress at the very edge of the hole. If elements further from the holes were chosen for the investigation, the stress would have had the space to redistribute and therefore would have represented less clearly the stress distribution around the holes. In addition, to study properly the concentrations of stress at the edge of the holes, the element size has been chosen

through a convergence analysis to obtain the best compromise between validity of the results and analysis run-time.

3.2.3. Stress distribution graphs

To visualise the results, a series of 3D stress graphs are used. These represent the stress versus depth of the ply (Figure 3-1. a) and angular positions around the hole (α) (Figure 3-1. b). All the results are organised in curves, each one showing the stresses for a single ply. A colour code is used to highlight the orientation of each ply and in which plate that ply is located. The six stress components (σ_1 , σ_2 , σ_3 , τ_{12} , τ_{13} and τ_{23}) in the local coordinate system of the composite material in each ply (where direction 1 is the direction of the fibres and direction 3 the through-the-thickness direction) are reported. Plate 1 is defined as the plate containing the countersink hole (countersunk-head side) and plate 2 is the plate containing the completely cylindrical hole (nut side). In each graph, the angular position $\alpha=0$ corresponds to the bearing plane of the plate analysed.

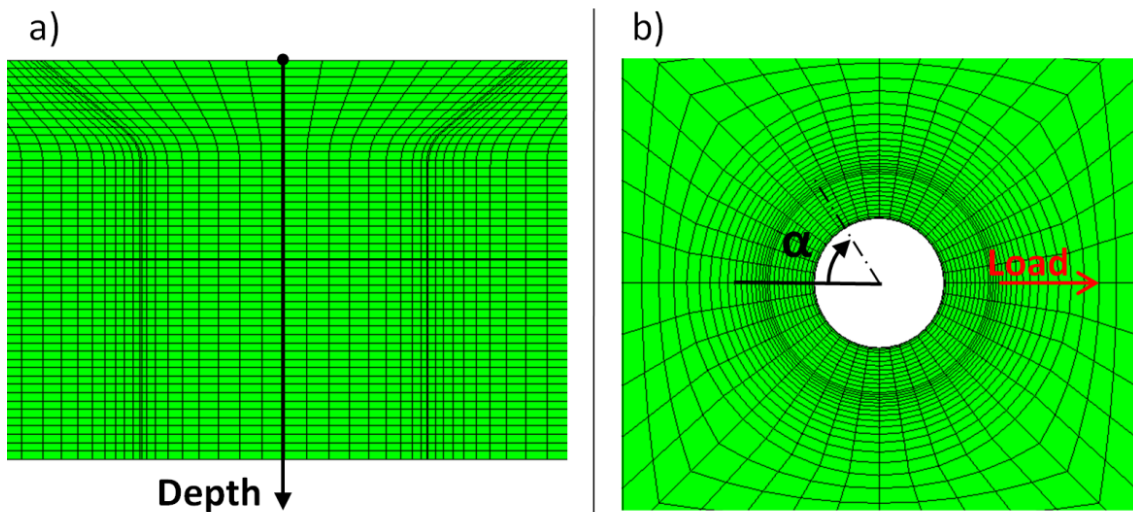


Figure 3-1. Axis definition in stress graphs: a) Depth of the elements(distance from top surface). b) Angular position of the elements.

3.3. Problem definition

3.3.1. Strategy

Several configurations of composite single-lap bolted joints with countersunk bolts have been analysed following the method described in the previous section. To investigate the stress distribution in detail around the holes of a composite bolted joint, a reference joint configuration is chosen and analysed. The stress distributions around the holes are obtained and discussed, and the stress components most relevant for the initiation of bearing damage are identified. To study the effect on the stress distribution of the head height of the countersunk bolt, of the clearance between bolt shank and holes, and of the position in the plate of the countersunk bolt head, other joint configurations are analysed varying only the studied parameters with respect to the reference configuration.

3.3.2. Reference configuration

Figure 3-2 shows the geometry of the reference joint and a detail on the countersunk bolt used. The reference joint is equipped with two EN bolts (with head height 1.88 mm). This bolt has been chosen since it is fairly commonly used in the aeronautical industry. The clearance shank-hole is equal to 0.06 mm. The materials used in the reference joint model, as well as in all the other joint models analysed, are unidirectional CFRP T800/M21 (ply thickness= 0.184 mm) for the plates, and Ti6Al4V and stainless steel for bolts and nuts respectively. The mechanical properties of the T800/M21 [83] are listed in Table 3.1 and are produced following the standards [84] and [85].

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Table 3-1. Mechanical properties of the T800/M21 composite material [83].

Unidirectional T800/M21		
Ply thickness = 0.184 mm		
<i>Mechanical property</i>	<i>Sym.</i>	<i>Value</i>
<i>Longitudinal modulus</i>	E₁	160.4 GPa
<i>Transverse modulus</i>	E₂	9.29 GPa
<i>Through-thickness modulus</i>	E₃	9.29 GPa
<i>In-plane shear modulus</i>	G₁₂	4.2 GPa
<i>Transverse shear modulus</i>	G₁₃	4.2 GPa
<i>Through-thickness shear modulus</i>	G₂₃	3.1 GPa
<i>Major Poisson's ratio</i>	ν₁₂	0.33
<i>Major transverse Poisson's ratio</i>	ν₁₃	0.33
<i>Through-thickness Poisson's ratio</i>	ν₂₃	0.5
<i>Longitudinal tensile strength</i>	X_T	3067 MPa
<i>Longitudinal compressive strength</i>	X_C	1390 MPa
<i>Transverse tensile strength</i>	Y_T	43.9 MPa
<i>Transverse compressive strength</i>	Y_C	250 MPa
<i>Through-thickness tensile strength</i>	Z_T	43.9 MPa
<i>Through-thickness compressive strength</i>	Z_C	250 Mpa
<i>In-plane shear strength</i>	S₁₂	102.6 Mpa
<i>Transverse shear strength</i>	S₁₃	56.3 MPa
<i>Through-thickness shear strength</i>	S₂₃	95 MPa

The stacking sequence used for each plate is quasi-isotropic [(45,-45,0,90,45,-45,0,90,-45,45,0,90)]_s, leading to a total of 24 plies and a plate thickness of 4.416 mm.

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The bolt diameter is 6.35 mm and the countersunk head angle is equal to 100° . Since this study has its main focus on bearing damage, the geometrical relations between the bolt diameter and the plate dimensions were chosen to avoid shear-out and net-section failures ($e/d=4$ and $w/d=8$).

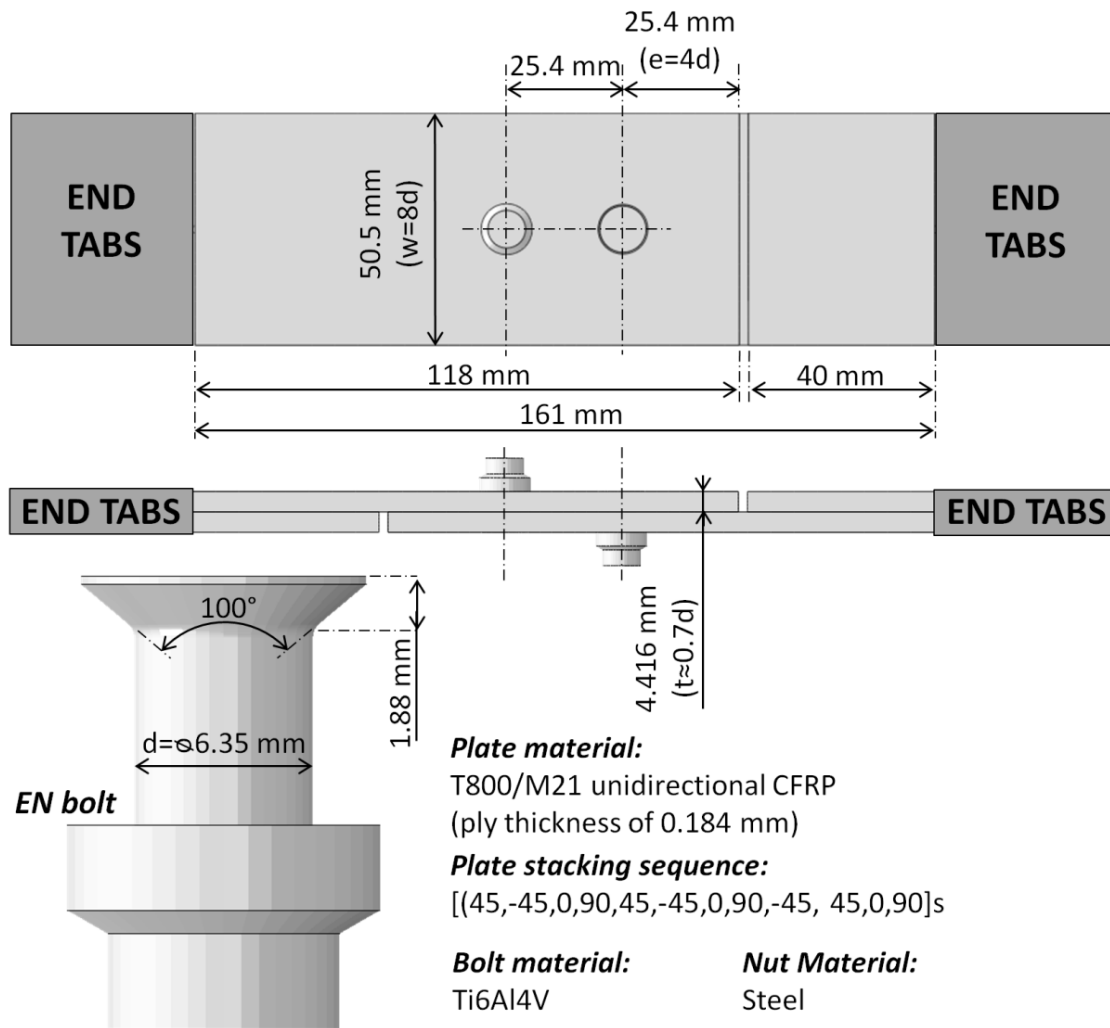


Figure 3-2. Geometry and details of the reference CFRP bolted joint.

The clamping force applied to each bolt, during the first analysis step, is equal to 10 kN, as recommended in [86]. The coefficients of friction used are 0.32 for the composite-composite contact and 0.13 for the contact between composite material and metal.

The tensile load applied to the joints, at which the stress distributions are studied, has been selected with the use of experimental static test results. The tests were performed on specimens identical to the reference joint. The selected load is the one corresponding to the onset of the major loss of joint stiffness caused by bearing (Figure 3-3). Even though it is possible, if not likely, that a limited amount of damage could develop earlier, that load has been chosen since this study aims to analyse the stress state at the start of major damage accumulation due to bearing.

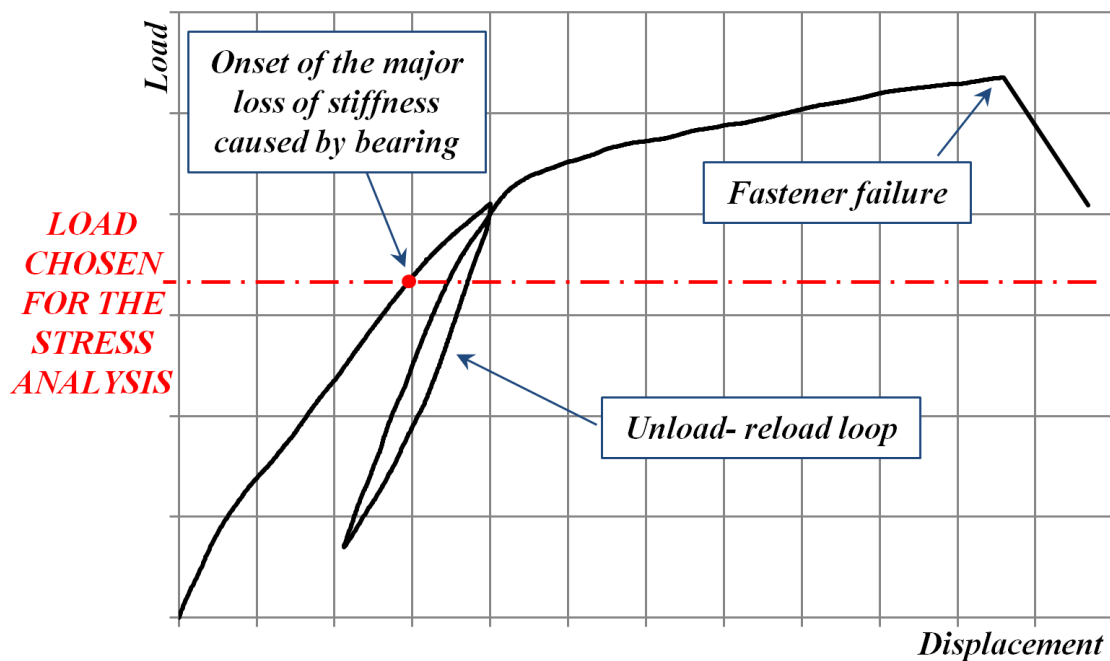


Figure 3-3. Analysis load selected from experimental load-displacement curve of a static test on the reference joint. This is the load found at the onset of the major stiffness loss caused by bearing.

3.3.3. Parametric studies

Each joint analysed in the parametric studies is identical to the reference configuration with the exception of the studied parameters. The studied configurations are summarised in Table 2. The investigated parameters are:

1. The head height of the countersunk bolt (Figure 3-4). The four analysed heights are 1.55, 1.88, 2.74 and 3.2 mm. The plate thickness is kept constant (4.416 mm), therefore the head height/plate thickness ratios (h/t) of the analysed bolts are 0.35, 0.43, 0.62, 0.72 respectively. The first three heights correspond to commercially available bolts (the second is the bolt studied in the reference joint), while the last, and highest, height has been chosen to study the case of a bolt head height comparable to the thickness of the plate.

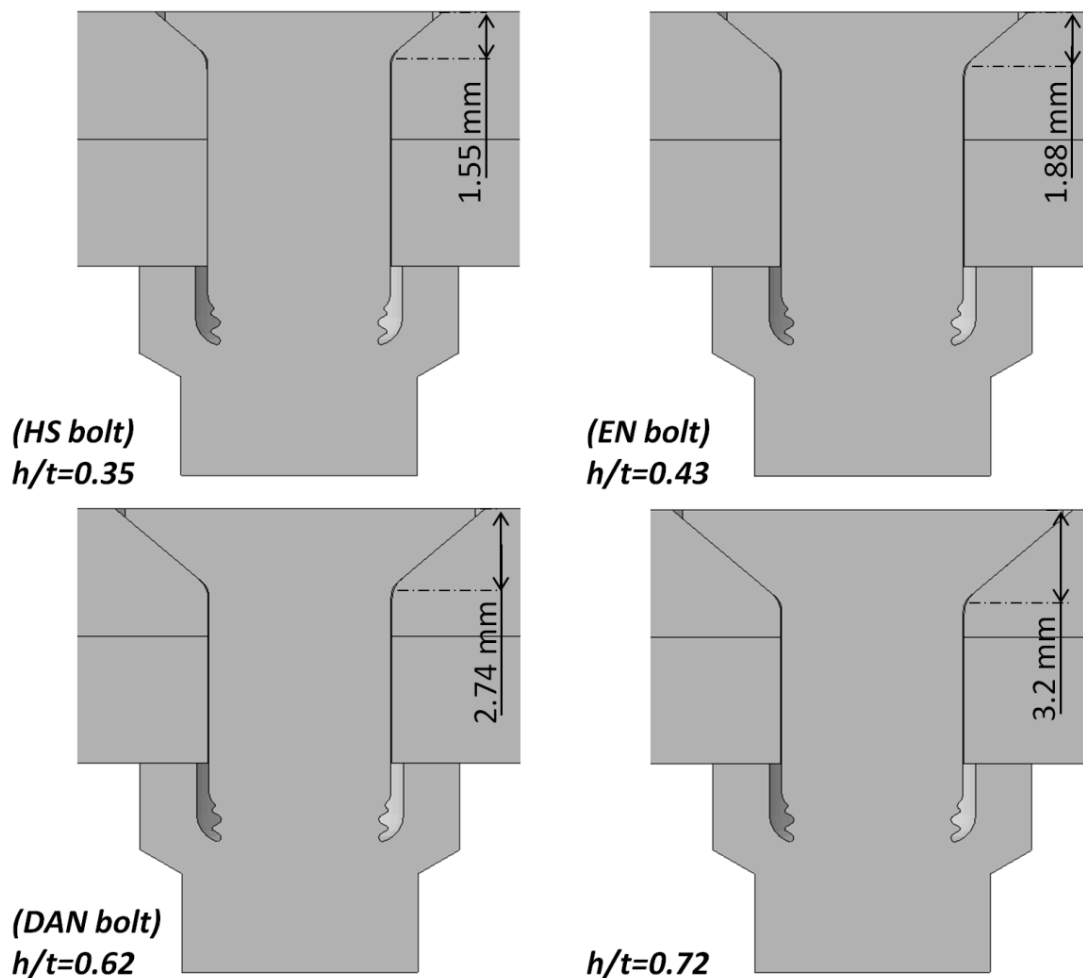


Figure 3-4. Bolts of the four joint configurations analysed to study the effect of the bolt head height on the stress distribution around the holes.

2. The clearance between bolt shank and holes. The analysed clearances are 0, 0.06 and 0.15 mm (defined as differences between shank and hole diameters). These correspond to a perfect fit, an average condition and a relatively large clearance fit, respectively. The bolt used is the same used in the reference joint while the hole diameters of both plates are varied to create the desired clearance. The 0.06 mm clearance case is already analysed in the reference joint.
3. The position in the plate of the countersunk bolt head (Figure 3-5). Two joint configurations, identical to the reference configuration but equipped with either HS or DAN bolts, are compared with the corresponding configurations with an opposite head position. In the first two configurations, the head is located next to the plate run-out (run-out heads), while, in the other two configurations, it is positioned towards the interior of the plate (plate-interior heads). The configurations are equipped either with relatively small or big heads (HS and DAN respectively) to compare the effects on the stress distribution of the head height between joints with run-out heads (as in the head height parametric study) and joints with plate-interior heads.

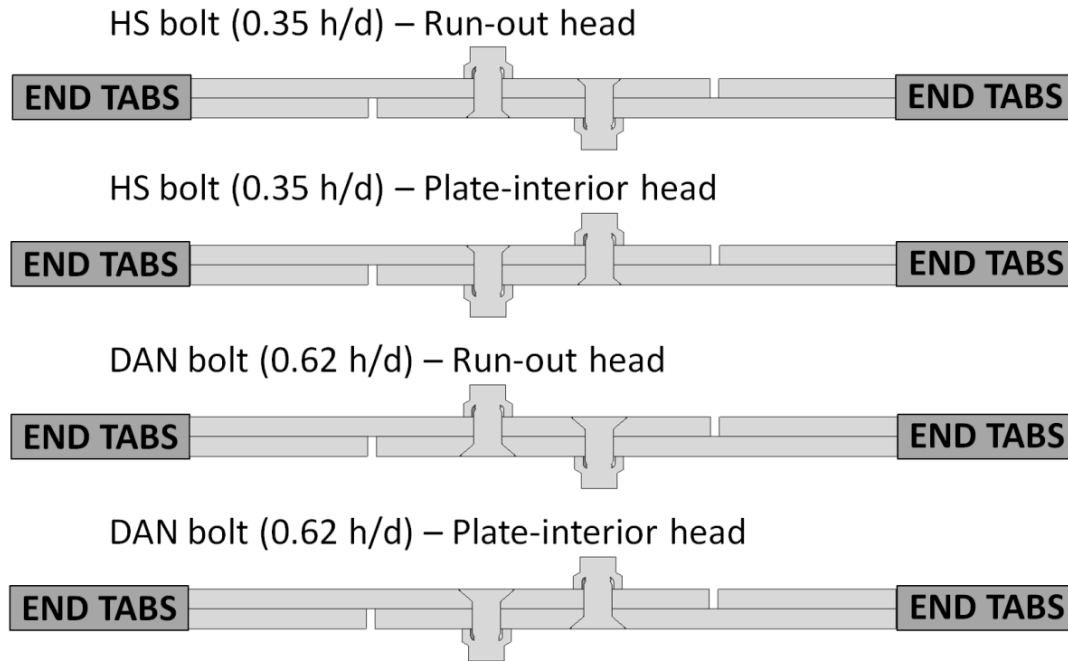


Figure 3-5. Four joint configurations analysed to study the effect of the bolt position on the stress distribution around the hole and the influence of the head height on it.

Table 3-2. Summary of the investigated bolted joint configurations. The number under brackets indicates the equality with the configuration identified by that number.

Conf.	Configuration name	Plate thickness	Head height	Clearance	Head position
Reference configuration					
1	Reference (EN bolt)	4.416 mm	1.88 mm	0.06 mm	Run-out
Head height parametric study					
2	HS bolt (1.55 mm)	4.416 mm	1.55 mm	0.06 mm	Run-out
3 (1)	EN bolt (1.88 mm)	4.416 mm	1.88 mm	0.06 mm	Run-out
4	DAN bolt (2.74 mm)	4.416 mm	2.74 mm	0.06 mm	Run-out
5	3.2 mm	4.416 mm	3.2 mm	0.06 mm	Run-out
Bolt shank–hole clearance parametric study					
6	Clearance = 0 mm	4.416 mm	1.88 mm	0 mm	Run-out
7 (1)	Clearance = 0.06 mm	4.416 mm	1.88 mm	0.06 mm	Run-out

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8	Clearance = 0.15 mm	4.416 mm	1.88 mm	0.15 mm	Run-out
Head position study					
9 (2)	HS bolt, run-out	4.416 mm	1.55 mm	0.06 mm	Run-out
10	HS bolt, plate-interior	4.416 mm	1.55 mm	0.06 mm	Plate-int
11 (4)	DAN bolt, run-out	4.416 mm	2.794 mm	0.06 mm	Run-out
12	DAN bolt, plate-interior	4.416 mm	2.794 mm	0.06 mm	Plate-int.

3.4. Stress analysis of the reference joint

3.4.1. Results

Figure 3-6 and Figure 3-7 shows the distributions of the six stress components around the holes of the composite joint chosen as reference for the following studies. σ_1 is the stress component which reaches the highest values. Figure 3-6a shows the σ_1 distribution, for both plate 1 and 2: a progressive increase of σ_1 , through the plates' thickness, going towards the faying surface can be observed. In plate 1, the locations with the highest σ_1 tensile stresses are in the 45° and -45° oriented plies, which are also the closest plies to the faying surface, at an angle α of -45° and 45° respectively. In the same plate, the highest σ_1 compressive stress is found in the first 0° oriented ply from the faying surface. In plate 2, the highest tensile stresses are found, differently from plate 1, in the 0° oriented ply closest to the faying surface, at an angle α of +90° and -90°. In the same plate, the compressive stress peak is located in the same ply as the tensile peak; but at an angle α of 0°.

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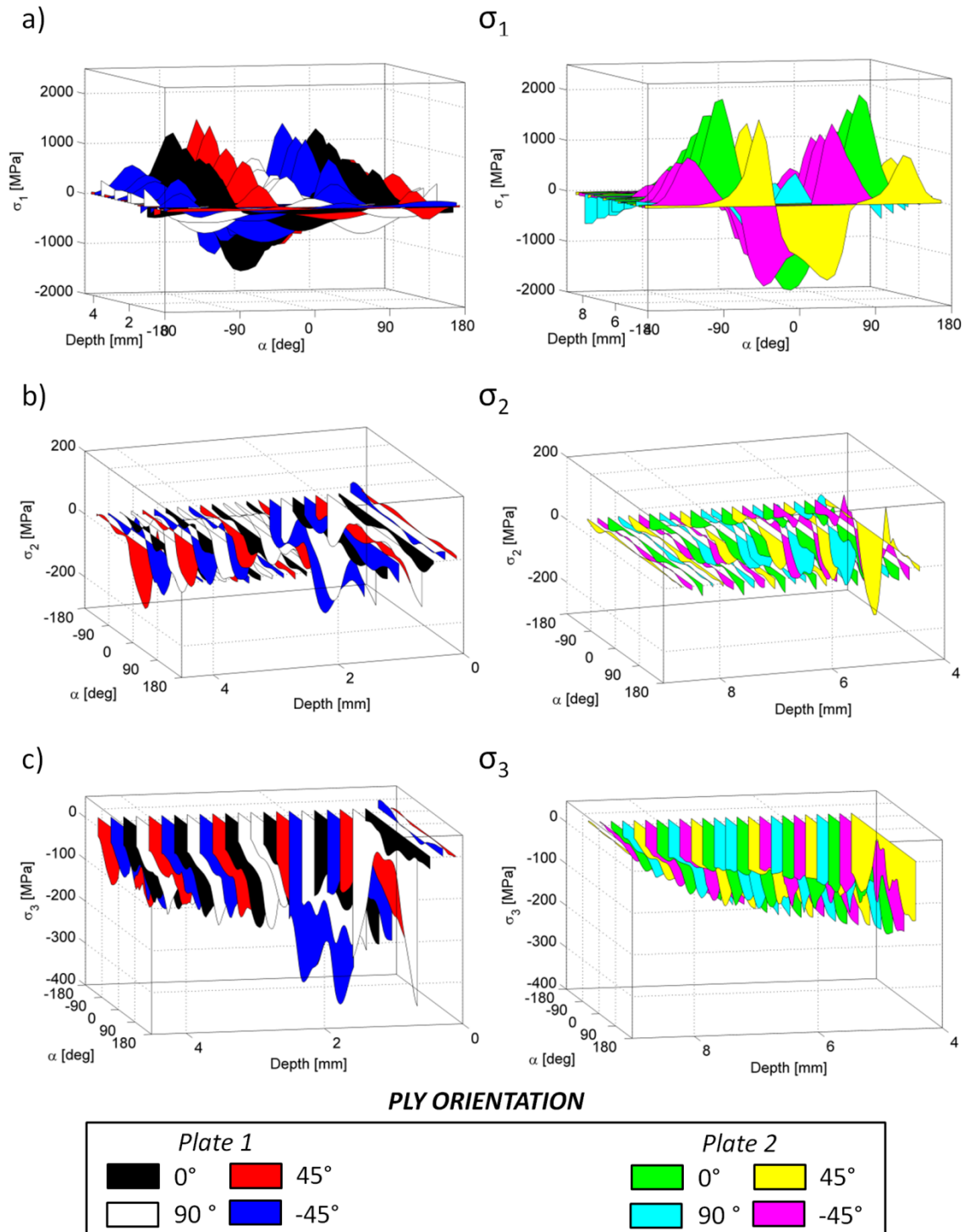


Figure 3-6. Distribution of the stress components ($\sigma_1, \sigma_2, \sigma_3$) around the holes of the reference joint when under tension loading. (Plate 1 – plate with countersink hole, Plate 2 – plate with straight hole)

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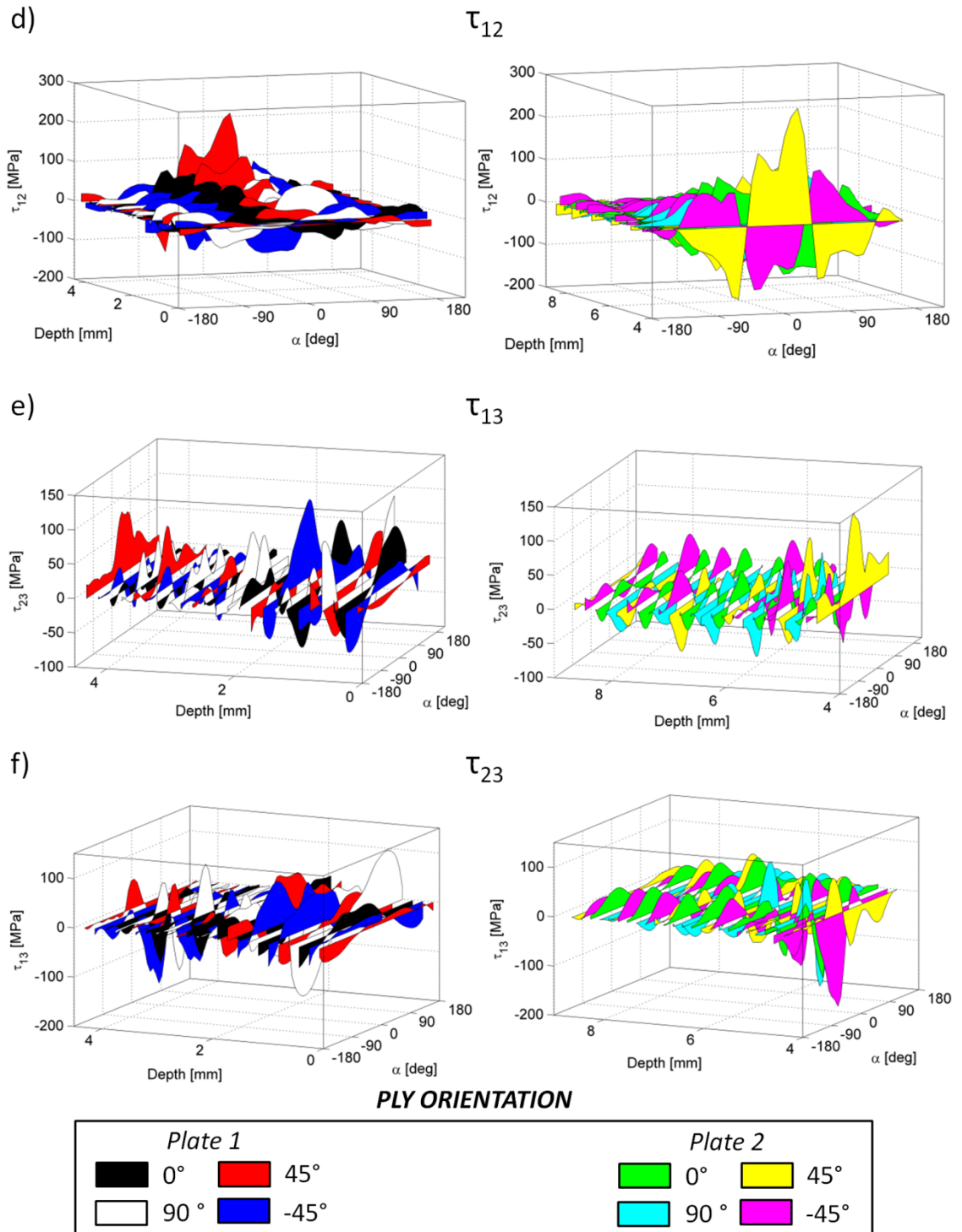


Figure 3-7. Distribution of the stress components (τ_{12} , τ_{13} , τ_{23}) around the holes of the reference joint when under tension loading. (Plate 1 – plate with countersink hole, Plate 2 – plate with straight hole)

Figure 3-6b shows the σ_2 distribution and highlights that almost all plies are completely in transverse compression. The presence of the countersink is clearly visible in plate 1: the plies involved in the contact countersink-countersunk head have generally higher stress values, with a peak around $\alpha=0^\circ$. In both plates, σ_2 increases when approaching the faying surface, and shows a peak at about an angle of $\alpha=0^\circ$ in plate 1 and plate 2. Even though all plies follow this trend, the 90° , 45° and -45° oriented plies reach relatively higher values (with the 90° plies slightly above the others) than the 0° oriented plies, especially in plate 1.

As shown in Figure 3-6c, the plies are almost completely under through-the-thickness compression, and the distribution of σ_3 around the holes is much more homogenous than in the case of the previous stress components. The effect of the countersink is clearly visible in Figure 3-6c, as seen in σ_2 (Figure 3-6b). Slightly higher σ_3 is found at about an angle $\alpha=0^\circ$ in plate 1 and plate 2.

In Figure 3-7d, the in-plane shear stress τ_{12} does not appear to exhibit a clear pattern in its distribution. Despite this, slightly higher stresses are noticeable at about an angle $\alpha=0^\circ$ in plate 1 and in plate 2. Once more, the plies appear to develop a higher stress when approaching the faying surface.

In Figure 3-7e, the transverse shear stress τ_{13} is higher in the plies which are part of the countersink. In plate 2, the increase of stress towards the faying surface is very clear and the highest stresses are found at about an angle $\alpha=0^\circ$. The same increment is found to a lesser extent also in plate 1 with a maximum at about an angle $\alpha=0^\circ$.

In Figure 3-7f, the transverse shear stress τ_{23} does not show a clear trend in its distribution. Despite this, a higher stress is still visible in the plies affected by the countersink.

3.4.2. Discussion

Most graphs in Figure 3-6 show a clear higher stress state at an angle $\alpha=0^\circ$ in plate 1 and in plate 2. The reason can be gleaned from Figure 3-8: under the effect of the load applied to the joint, the clearance between the bolt shank and the holes is closed. This allows the contact between the parts and therefore the exchange of load.

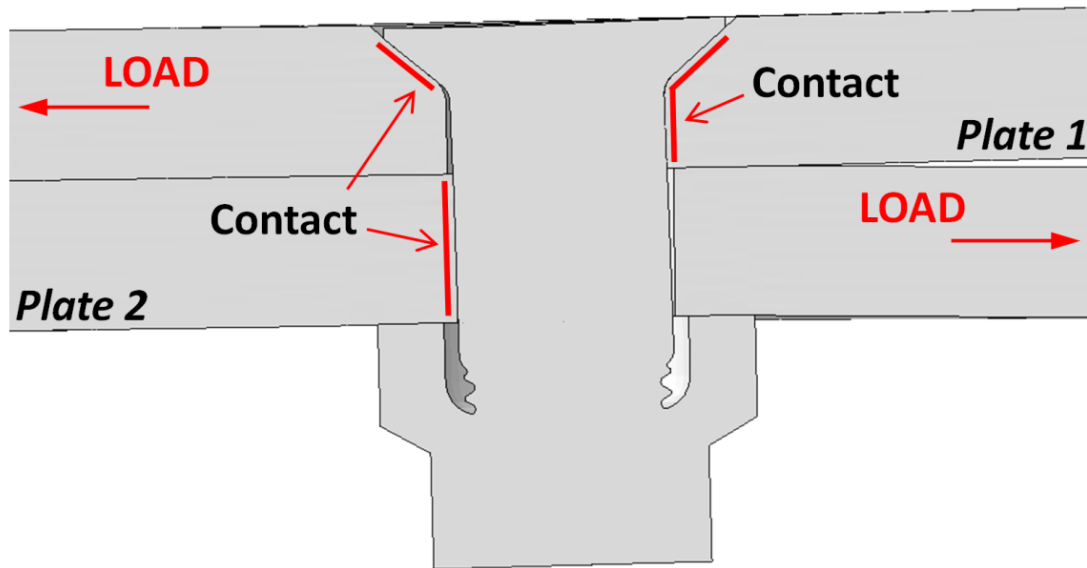


Figure 3-8. Contact surfaces between the bolt and the holes of the two plates.

A strong increase of the stress, through the thickness and going towards the faying surface, has been clearly seen for most stress components. This behaviour obviously does not agree with the concept of bearing stress [5], where the stress on half of each hole is considered homogenous. Despite the very broad use of this concept, its use results in a simplified, and not conservative, assessment of the stress state of the material around the hole. The distribution of pressure in the contact between shank and hole, in the case of a single lap composite joint with protruded bolts, has been studied by Ireman [16]. This study highlights a pressure peak at the faying surface. Egan et al. [60] studied the distribution of the tangential and radial

stress around the hole of a single lap composite joint with countersunk bolts. The main reason for the peak of stress and pressure, highlighted in the referenced works, is the strong anti-symmetric geometry of the single lap joints. In addition to this, the compliance of the parts in contact and the presence of clearance make the tilting of the bolt shank inside the holes possible and then the contact takes place only on a limited surface. The previous chapter showed that the first contact between shank and holes takes place at the faying surface, and that the contact areas grow when increasing the load applied to the joint. The limited area of the contact surfaces forces most of the load applied to the joint to be transferred through a limited portion of material and, therefore, creates stress concentrations in that material.

While the plate exhibit regions both in longitudinal tension and in longitudinal compression, in the transverse and in the through-the-thickness direction, the holes are almost totally in compression. The through-the-thickness compression is due to the clamping force applied to the bolts. The σ_3 distribution around the holes is almost constant since the stiffness in the thickness direction is not influenced by the ply orientation. The deviation from this constant stress value in some plies of plate 1 is attributed to the presence of the countersink: an important share of the clamping force is transferred from the head to the countersink through a limited surface around the first point of contact between the parts (Figure 3-9). The corresponding high pressure creates a higher level of stress in the plies of the area. The decreasing level of σ_3 in the outer plies of plate 2 is instead attributed to a shear lag effect: the nut is in contact with the plate outside the ring of elements analysed (Figure 3-10). Due to this geometrical discontinuity, the stress, from an almost null value at the outer ply, increases in the subsequent plies until reaching the stress value of the rest of the plate.

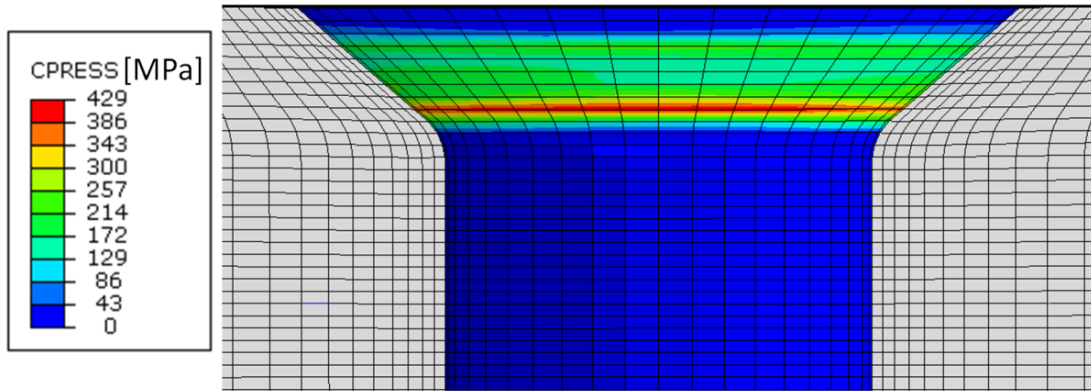


Figure 3-9. Pressure distribution in the countersunk head-countersink hole contact after the clamping force is applied to the bolt.

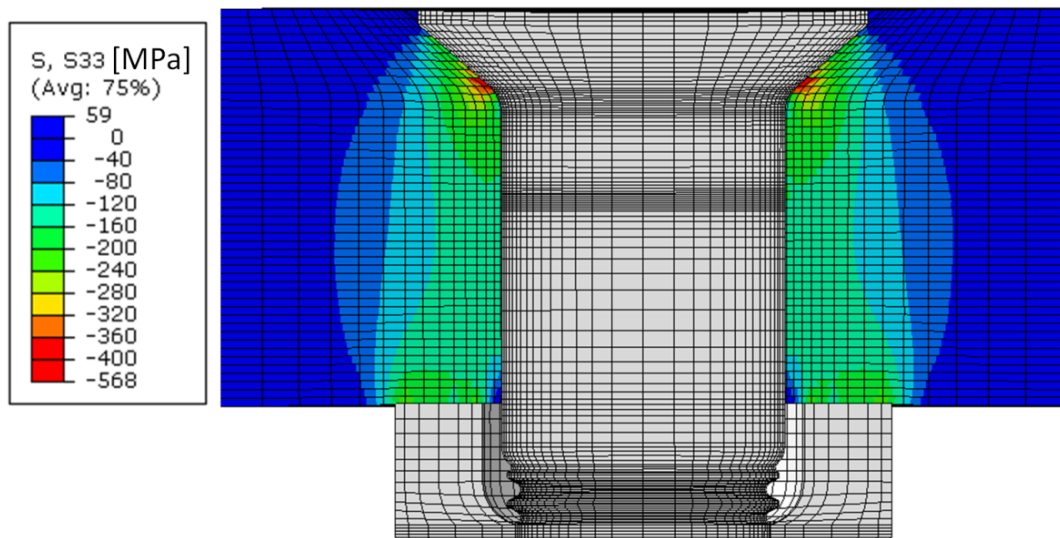


Figure 3-10. Distribution of σ_3 through the section of the reference joint after the clamping force has been applied to the bolt.

The longitudinal stress σ_1 , appears to have a key role in the bearing damage process: σ_1 is the stress component which reaches the highest values in compression and, due to the high stiffness in the fibre direction, is the one which contributes the most to carry the load transferred by the bolts. For this reason, fibre failure, and the consequent loss of stiffness in the fibre direction, would cause a strong increase in the other stress components and probably trigger other types of failures. Comparing the

maximum values reached by each stress component, even if these may have some degree of mesh dependency, with the corresponding strength, it is possible to see that σ_1 , in compression, exceeds its relative strength and Figure 3-6a correctly predicts bearing failure at the location where it is experimentally observed. In addition, the values of σ_2 and σ_3 in the plies close to the faying surface, where the bearing damage takes place, are similar to or lower than in the countersink region, where significant damage has not been found. This seems to suggest that σ_2 and σ_3 are not the stress components driving the bearing damage, although it cannot be excluded that they may have a role in the process. Some previous works have studied the bearing damage experimentally and agree on the fundamental role of σ_1 and compressive fibre failure. Several research groups [54-56] have found that the initiation of bearing damage consists of fibre compressive failure in the 0° oriented plies, at the edge of the holes, closely followed by fibre kinking in the same plies. As consequence of the increasing load applied to the joint, the number of fibre kinks increases and the laminates start developing through-the-thickness shear cracks from, and connecting, the fibre kinks. In parallel to the formation of shear-cracks, the plates develop delaminations starting from the fibre kinks in the 0° oriented plies, with the kinks effectively working as initiators of this type of damage.

The importance of σ_1 in the bearing damage process, as highlighted, warrants a more detailed examination. Figure 3-11 shows the distribution of σ_1 from a different viewpoint, illustrating clearly the variation of the stress through the thickness of the plates. In this graph, the peak of σ_1 varies almost linearly for all the plies of a given orientation from a near-to-zero value, in the external plies, to its maximum value, close to the faying surface. A small deviation from this pattern can be observed in the form of an increase in stress in the first plies of the countersink (which is caused by the contact with the countersunk bolt head). Even though the first plies from the faying surface, in both plates, are 45° and -45° oriented plies, these exhibit lower compressive stresses than the following 0° ply, which is further from the faying surface. This ply is

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considerably more stressed than the following 0° plies and its failure is likely to cause a sudden loss of stiffness in the joint and the start of the bearing damage process.

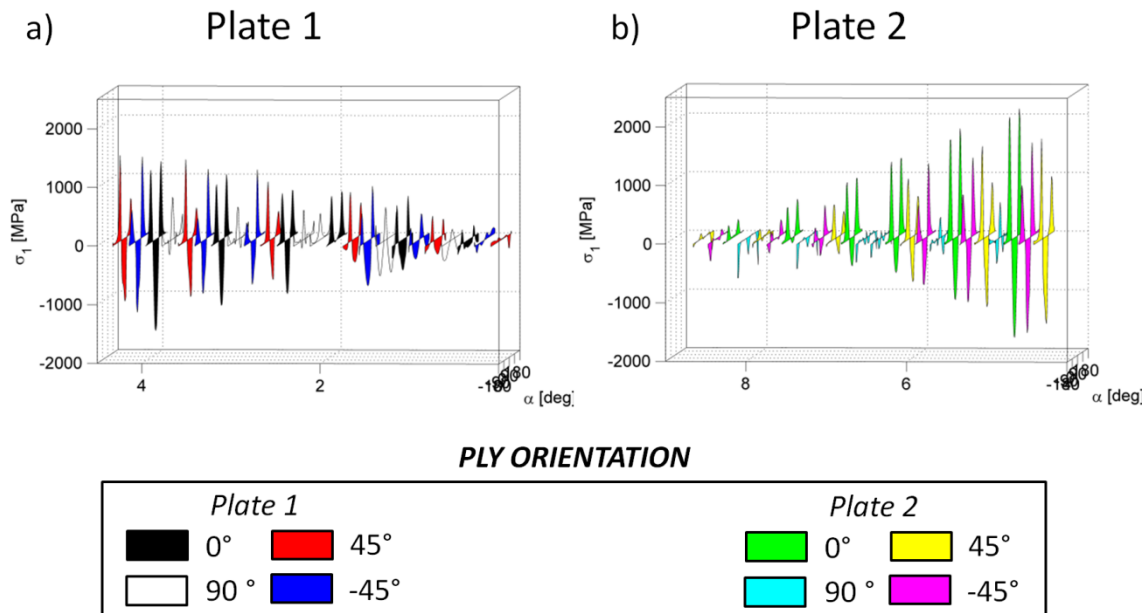


Figure 3-11. Detail on the through-the-thickness distribution of σ_1 around the holes of the reference joint when under tension loading. (Plate 1 – plate with countersink hole, Plate 2 – plate with straight hole)

Figure 3-12 shows how σ_1 varies angularly around the holes in plate 1 (a) and plate 2 (b). In plate 1, excluding the plies which are part of the countersink, the distribution of σ_1 is fairly clear. In both plates, the plies are in compression for angle α coincident with their respective orientation angles. They are, instead, in tension at an angle $\alpha = \pm 90^\circ$ from their respective orientation angle. This has the effect of creating a set of regularly spaced peaks in tension and in compression in the σ_1 distribution.

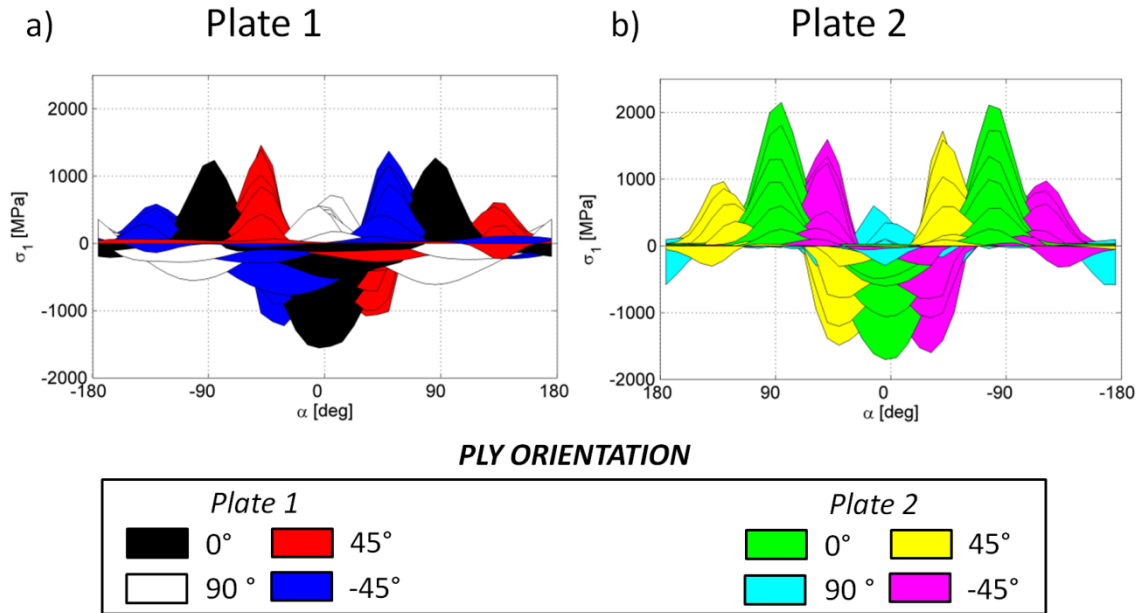


Figure 3-12. Detail on the angular distribution of σ_1 around the holes of the reference bolted joint when under tension loading. a) View from plate 1. b) View from plate 2. (Plate 1 – plate with countersink hole, Plate 2 – plate with straight hole)

There is a clear difference between the maximum stress values in plate 1 and 2, especially in tension: an analysis of this is given in the Head Position Study section.

3.5. Head Study

3.5.1. Results

Figure 3-13 shows the distribution of σ_1 around the holes of four composite joints with countersunk head heights of 1.55, 1.88, 2.74 and 3.2 mm, respectively. In Figure 3-14 the maximum values reached by each stress component around the holes of the four configurations are presented.

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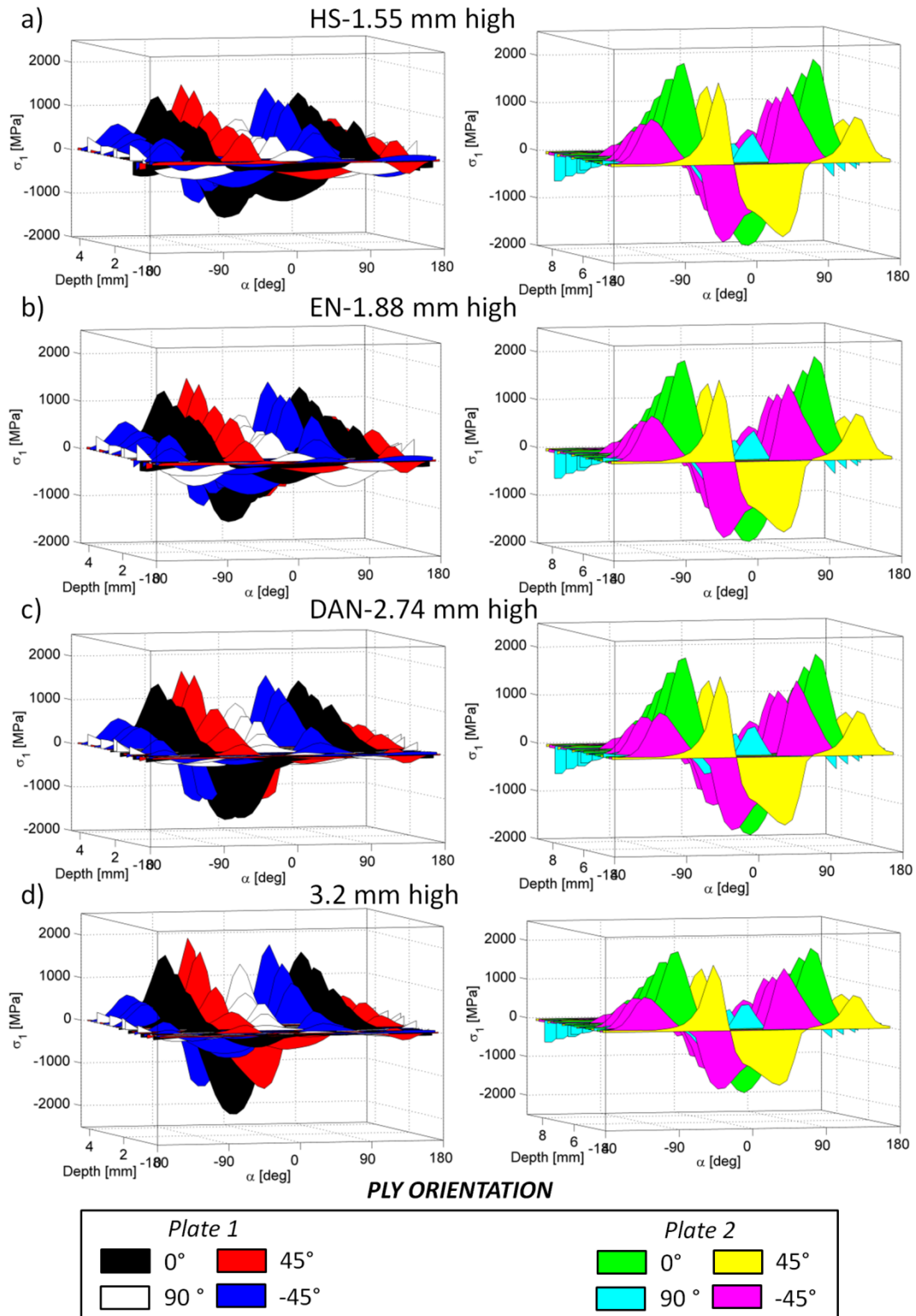


Figure 3-13. Distributions of σ_1 around the holes of joints (under tension loading) with different countersunk bolt head heights. (Plate 1 – plate with countersink hole, Plate 2 – plate with straight hole)

On the one hand the main features in the σ_1 distribution, analysed in the previous section, do not appear to change when varying the height of the head. On the other hand, varying the height of the head seems to have a strong effect on determining the maximum values reached by σ_1 . Figure 3-13 shows that the increase in the head height leads to a strong increase of the maximum values of σ_1 in plate 1, both in tension and compression, and, conversely, to a slight decrease, both in tension and compression, in plate 2. Figure 3-14 shows the magnitude of the described variations in the maximum values of σ_1 in the two plates of the four studied configurations. The same figure indicates that the maximum values of the other stress components vary less when incrementing the head height.

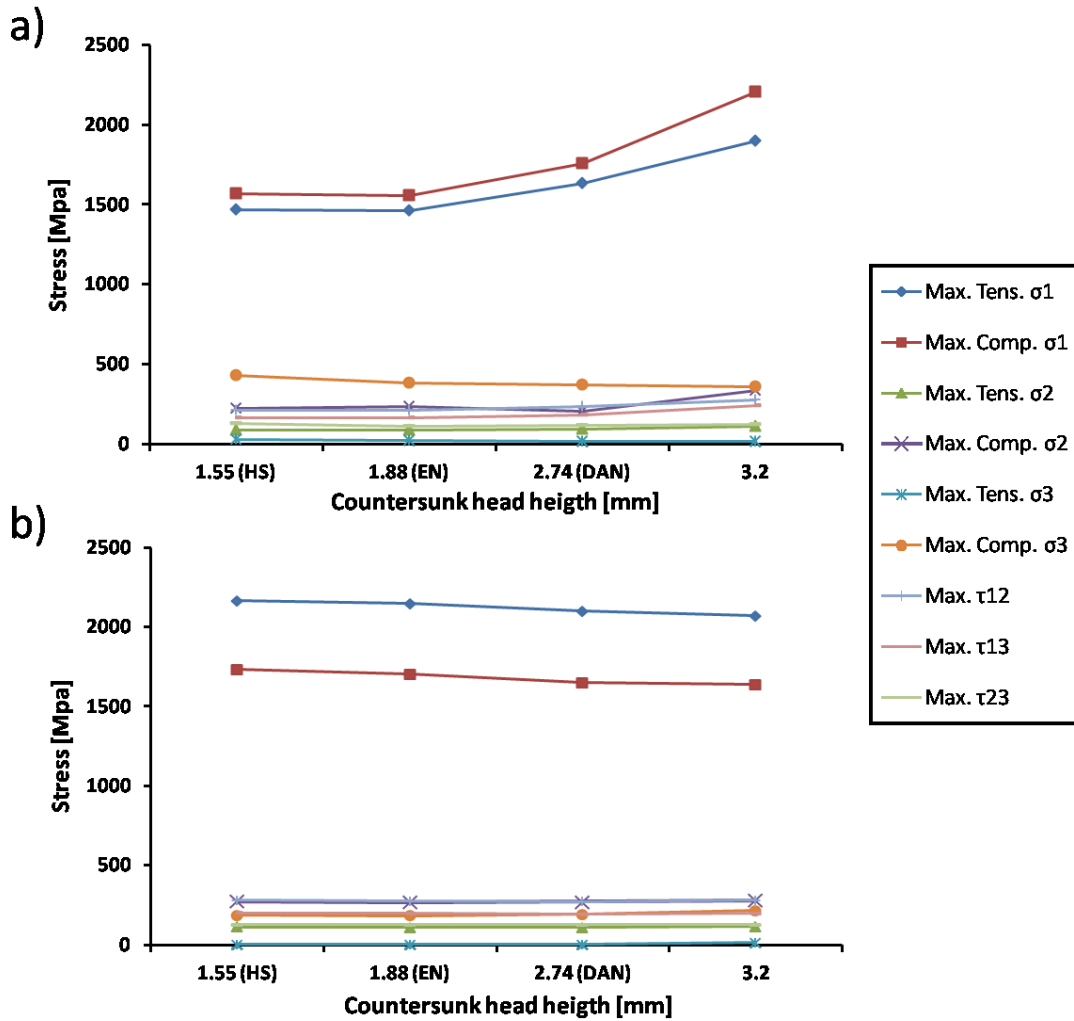


Figure 3-14. Maximum values of the six stress components around the holes of bolted joints with different countersunk head heights. a) Plate 1. b) Plate 2.

3.5.2. Discussion

Increasing the bolt head height, without changing the plate thickness, has the direct effect of increasing the extent of the countersink and, therefore, reducing the remaining cylindrical part of the hole. From the graphs analysed in the result section, it appears that only the 0° oriented plies which lie in the cylindrical part of the holes make a significant contribution, being highly compressed in the fibre direction, in sustaining the load transfer through bearing. This behaviour has been observed also by

Egan et al. [60], who analysed the radial stress around the countersink holes of single-lap single-bolt composite joints with countersunk bolts. In all four configurations analysed, an increase of stress towards the faying surface is clearly visible, as it was described in the previous section. Despite this, since the load applied to the joint, and therefore transferred through the bolts, is identical in all the configurations, a smaller number of 0° oriented plies carrying the load leads to a higher maximum stress in the first 0° oriented ply from the faying surface. This means that an oversized head, and therefore oversized countersink, could cause development of bearing damage in the plates at lower applied loads than smaller heads.

The σ_1 tensile maximum values are affected as well by the head height and the corresponding size of the countersink. Even around a completely cylindrical hole, a stress concentration is created and is caused by the geometrical discontinuity that the hole creates in the plate. In addition, the bigger the countersink, the less material is left to carry the load in the remaining cylindrical part of the hole. This effectively creates a second concentration of stress around the hole with the result of having higher σ_1 tensile maximum stresses when increasing the bolt head height.

As opposed to what was observed in plate 1, the maximum tensile and compressive σ_1 values in plate 2 appear to have a mild decrease when the bolt height increases (Figure 3-13). This behaviour is not caused by a geometry (and stiffness) change, as seen in plate 1, since the hole geometry in plate 2 is not varied between the four analysed configurations. Analysing the σ_1 distributions in plate 2 for the four configurations, an increase of stress towards the faying surface is again visible in all of them. Despite this, increasing the head height leads to have smaller differences in stress between the plies: the plies closer to the faying surface reach lower stress values while the further plies result more stressed. This phenomenon could be attributed to the presence of a higher, and bigger, head which allows a more limited rotation of the bolt shank in the holes. Smaller shank rotation leads to a more homogeneous distribution of pressure in the contact hole-shank, therefore, to a more homogeneous σ_1 distribution and to slightly lower σ_1 maximum values in plate 2.

From this analysis of the plate, it may appear that the bearing strength and the final strength of the joint increase for a smaller countersunk head. However, this is not necessarily the case since decreasing the head height may make fastener failure more likely, in particular head failure (Figure 3-15).



Figure 3-15. Cracked countersunk bolt head in single-lap composite joint after tensile test.

3.6. Clearance Study

3.6.1. Results

The σ_1 distributions around the holes of the three composite joints with clearances of 0, 0.06 and 0.15 mm, respectively, are shown in Figure 3-16. Figure 3-17 summarises the maximum values reached by the stress components in each configuration.

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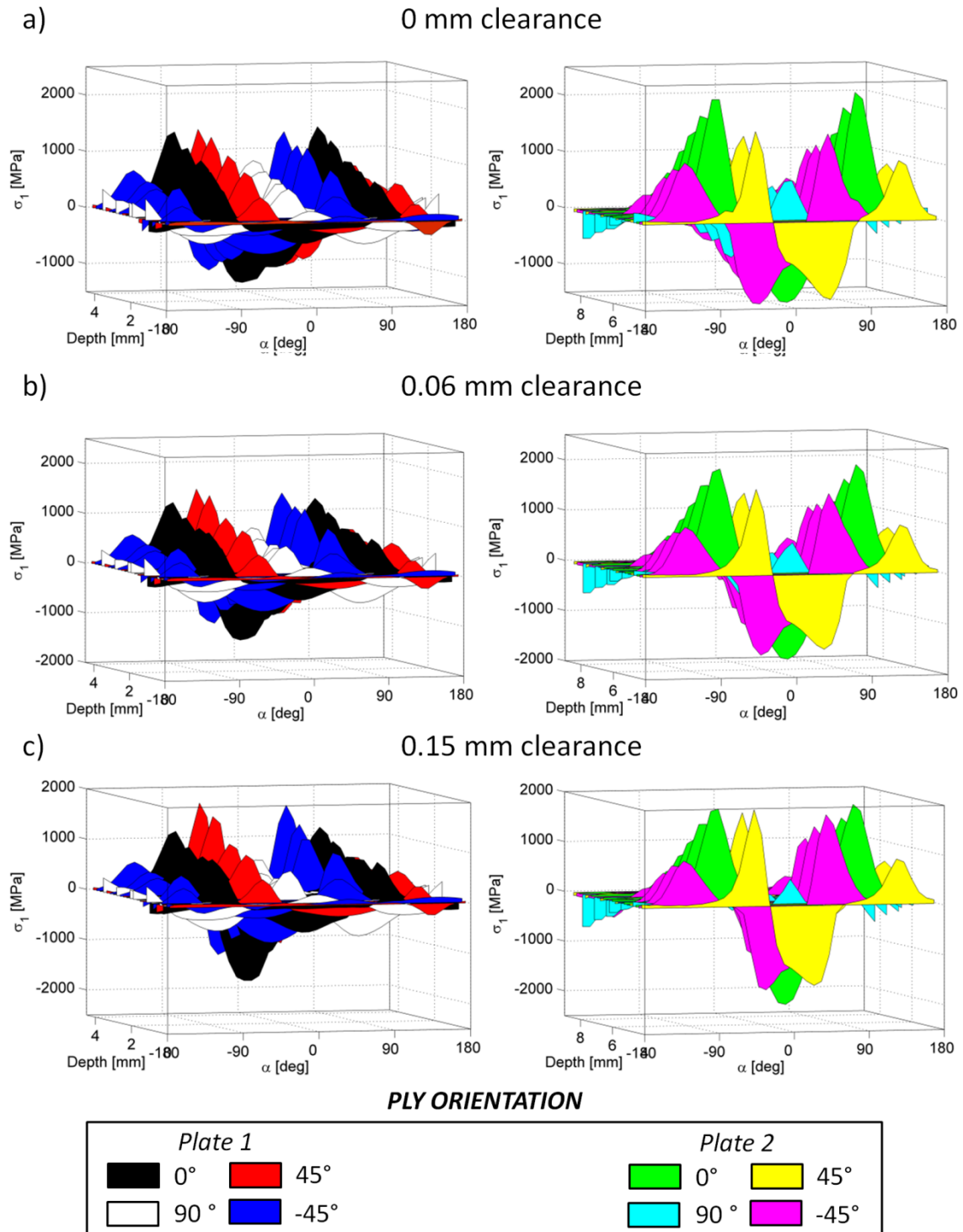


Figure 3-16. Distributions of σ_1 around the holes of joints (under tension loading) with different bolt shank-holes clearance. (Plate 1 – plate with countersink hole, Plate 2 – plate with straight hole)

The clearance does not appear to change the main features of the σ_1 distribution but influences the maximum values reached both in tension and compression. As opposed to what was seen when studying the effect of the head height, the clearance appears to influence the compressive stress of both plates in the same way. The main effect of increasing the bolt-shank clearance is a strong increase in the maximum values of the compressive stress in the 0° oriented plies. This has been observed also by Egan et al. [60], who analysed the distribution of radial stress in single-lap single-bolt composite joints with countersunk bolts. The tensile stress σ_1 in the $45^\circ/-45^\circ$ oriented plies has a similar increase, but in a lesser extent. In addition, higher clearances lead the maximum tensile σ_1 values to increase in the $45^\circ/-45^\circ$ oriented plies and to slightly decrease in the 0° oriented plies.

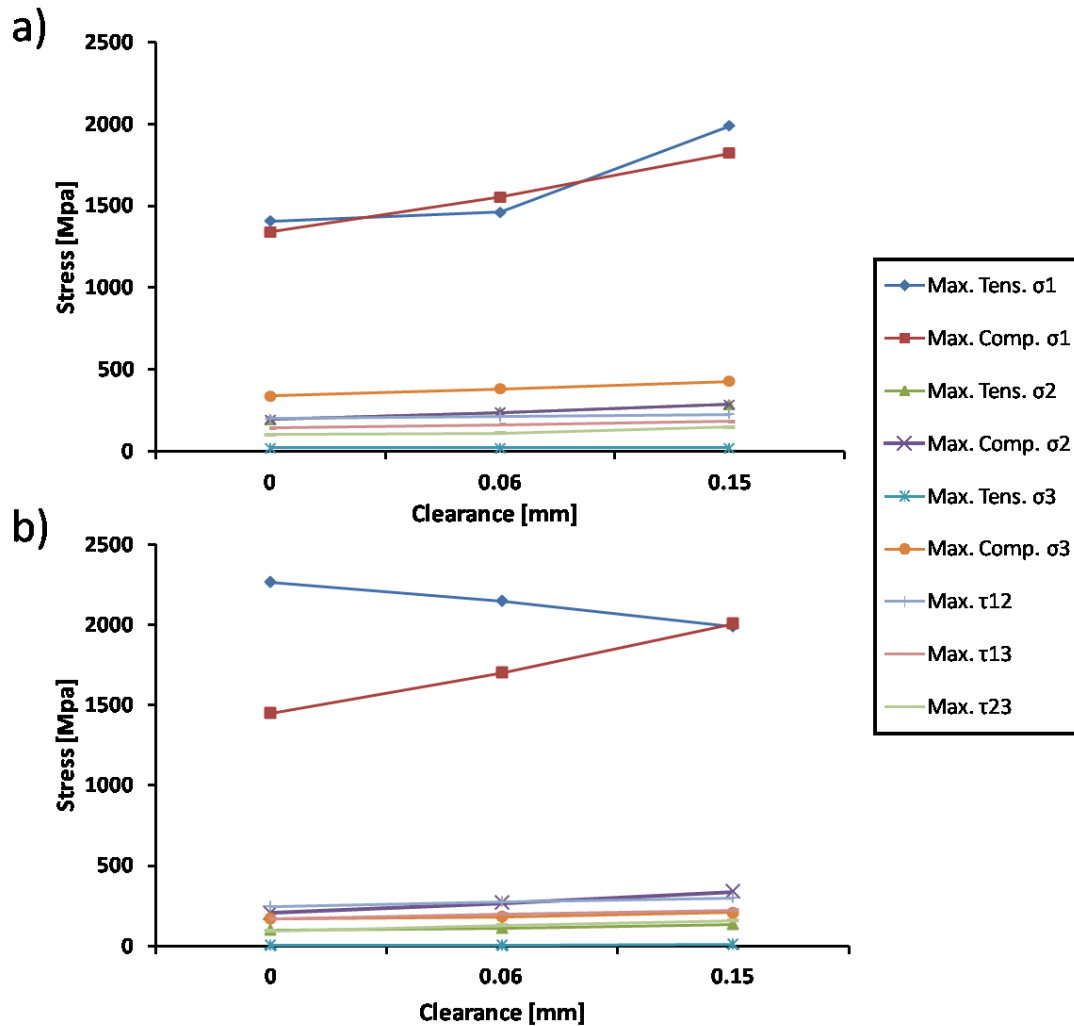


Figure 3-17. Maximum values of the six stress components around the holes of bolted joints with different clearance between bolts shanks and plate holes. a) Plate 1. b) Plate 2.

3.6.2. Discussion

Having a higher hole-shank clearance implies having a bigger difference between the diameters of hole and shank and having a larger gap between them. The different diameters cause the shank-hole contact to occur on a limited surface (and not on a line due to the compliance of the materials) and the gap between the parts allows the tilting of the shank inside the hole. These two phenomena lead to

progressively smaller contact surfaces when the hole-shank clearance increases. In Figure 3-18, the hole-shank contact surfaces in the three analysed joints are highlighted. These plots show that, when the clearance increases, the contact between the parts covers a more limited angle around the hole and that it becomes more localised towards the faying surface. The limited covered angle makes the compressive stress σ_1 to be localised on a smaller arc of material around the holes and, therefore, leads the stress peaks to be sharper and higher. The localisation towards the faying surface affects the distribution of the compressive stress σ_1 between the plies: if with a low clearance the compressive stress σ_1 increases almost linearly towards the faying surface, when the clearance increases the trend appears to become approximately exponential. This is particularly clear in the 0° oriented plies of plate 2. Here, increasing clearances leads the furthest plies from the faying surface to become, in compression, lightly stressed or not stressed at all.

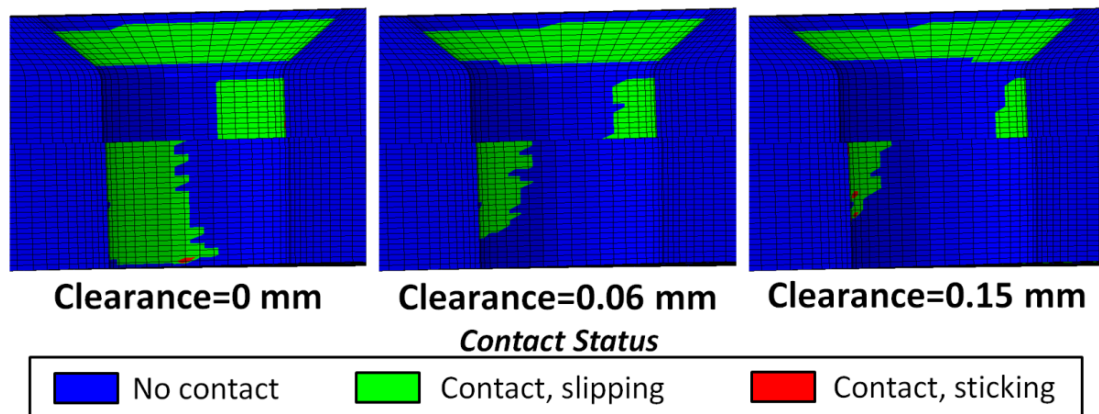


Figure 3-18. Reduction of the shank-hole contact surfaces with increasing clearances between bolt shank and holes in the plates (view from the joint section after having applied the tensile load).

The clearance appears to have an effect on the angular position of the compressive σ_1 peaks in both plates. In case of zero clearance, the compressive peaks in the 0° , 45° , and -45° oriented plies are located at an angle α approximately equal to the respective orientation angle of each ply. Increasing the clearance makes the stress

peak centres to progressively shift towards the centre of the contact (at $\alpha=0^\circ$). This is caused by the reduction of the angular extent of the contact surfaces.

The increase of the clearance, decreasing the extent of the contact surfaces, has the effect of reducing the stiffness of the entire joint when shank and holes are in contact. This is because, as observed, transferring a load through a smaller contact surface requires higher stresses and, therefore, higher deformations of the material in contact. This results in a more compliant connection between the parts and a reduction of the joint stiffness. The reduction of the joint stiffness caused by clearance has been previously highlighted experimentally and numerically by McCarthy et al. [59] and numerically in the previous chapter.

The increase of compressive longitudinal stress σ_1 , especially in the 0° oriented plies, with increasing clearances, could easily suggest that the bearing strength is strongly influenced by the bolt-hole clearance. A study conducted by McCarthy et al. [40] found out that its effect on the strength could be limited, at least until the clearance becomes particularly relevant. However, they observed that even if the bearing strength was only marginally reduced, the observed bearing damage was much more severe for high clearances. Figure 3-16 shows that higher clearances lead to higher compressive σ_1 . This, likely, lead to develop more bearing damage. From this point, It can be speculated that, after this first stage, the related deformation of the holes allows a wider contact between bolt and holes, with an increase of the extent of the contact surfaces. This would lead a more homogenous contact pressure and make the bolt-hole contact to behave similarly as if the clearance was effectively reduced, therefore, limiting the potential effect of clearance on the bearing strength.

Having more localised contact surfaces has also an effect on the maximum tensile σ_1 values in the 0° , 45° and -45° oriented plies of both plates. It is observed that, increasing clearances lead to higher maximum tensile σ_1 values in the 45° and -45° oriented plies. This appears to be caused by the reduction of the extent of the contact which strongly shrinks the area for the transfer of the load towards $\alpha=0^\circ$. In

order to diffuse this concentrated force to the rest of the plate and make it around the hole, the 45° and -45° oriented plies have to sustain the concentrated load and, then, transfer it to the 0° oriented plies at an angle α of 90° and -90° (Figure 3-19). For the same reason, increasing clearances leads to a slightly lower maximum tensile σ_1 in the 0° oriented plies: the concentration of stress at 90° and -90° is lower if the force is more concentrated and, therefore, angularly further from it. In this way, the 45° and -45° oriented plies have a longer distance for spreading the force in the net-section of the plate, reducing the stress concentrating at the edge of the hole.

The important role of the 45° and -45° oriented plies is confirmed by Ireman et al. [87], Par et al. [58] and Kretsis et al. [88]. In their investigations the bearing strength appears to increase when increasing the quantity of 45° and -45° oriented plies in the laminate, until reaching a maximum, and then decrease. In particular, Ireman et al. [87] found that the highest bearing strength was reached for about 65% of 45° and -45° , 20% of 0° and 15% of 90° oriented plies. This supports the hypothesised interaction between the 0° , and the 45° and -45° oriented plies: the former are loaded in compression and sustain all the load transferred by the bolt, the latter transfer the load from the former to the 0° oriented plies at the sides of the hole. The more the 45° and -45° oriented plies are efficient in transferring the load, the shorter the length in which the fibres of the 0° oriented plies need to be highly compressed, thus delaying the probability of formation of fibre kinking and maintaining the damage extent limited.

Even if in many papers, in figures summarising the possible joint failure modes, shear-out failure is schematically indicated to start at an angle $\alpha = 90^\circ$ and -90° , several research groups [8, 88-89] show this to initiate at an angle α of about 45° and -45° . In Figure 3-19, around $\alpha = 45^\circ$ and $\alpha = -45^\circ$, the -45° and 45° oriented plies respectively exhibit their maximum value of tensile σ_1 , while the other plies appear to be less stressed. This seems to suggest the important role of the 45° and -45° oriented plies in the shear-out failure mode: as mentioned earlier, these plies allow the transfer of load from the compressed fibres of the 0° oriented plies (at about $\alpha = 0^\circ$), where the load is

transfer through the bolt-hole contact, to the fibres in tension of the 0° oriented plies (at about $\alpha=90^\circ$ and -90°) (Figure 3-19), where the load is redistributed into the plate. If, because of the load transferred by bearing, tensile fibre failure occurs in the 45° and -45° oriented plies (at about $\alpha=-45^\circ$ and 45°), this load transfer becomes no longer possible. This leads to the development of shear-out cracks at about $\alpha=45^\circ$ and -45° and to the physical separation of the compressed and in-tension parts of the 0° oriented plies. In support to this theory, Prabhakaran [90] showed, with a photoelastic investigation, concentrations of stress at around $\alpha=45^\circ$ and -45° and their strong increase when reducing the e/d ratio, therefore linking these stress concentrations to shear-out failure. In addition, Sen et al. [8] studied the effect of the stacking sequence on the joint failure modes and showed that a reduction of 45° and -45° oriented plies in the stacking sequence leads to a more likely shear-out failure.

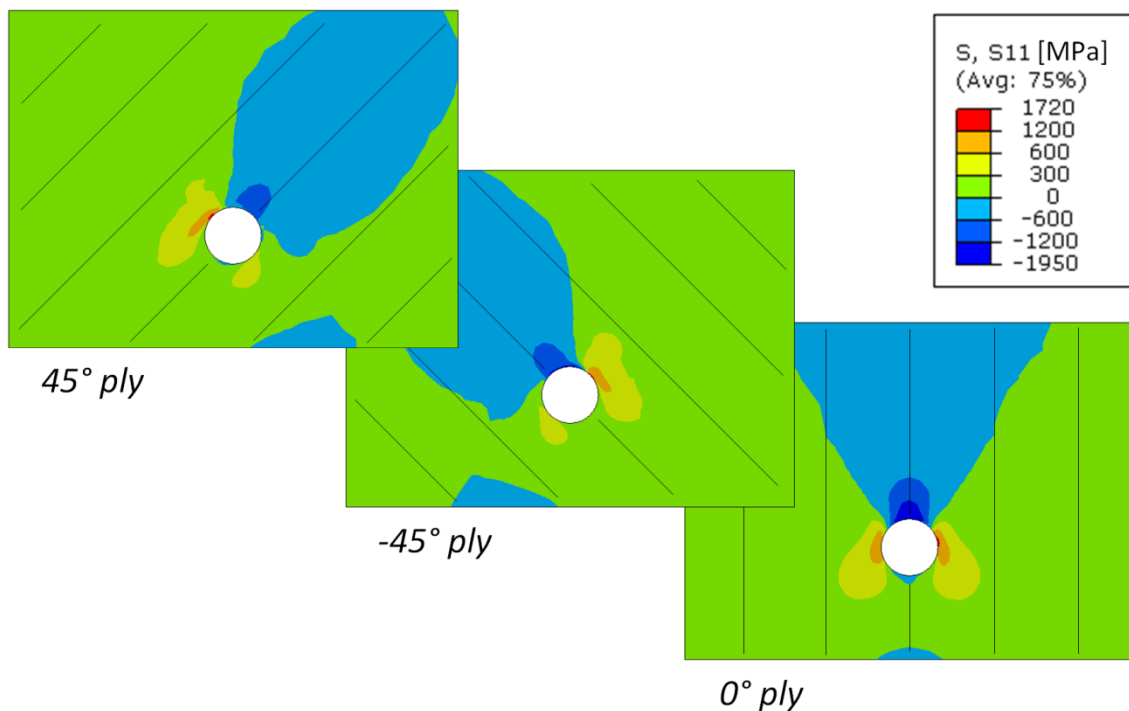


Figure 3-19. Distribution of σ_1 stress in the first plies from the faying surface (in the reference joint after the load has been applied) and role of 45° and -45° plies in transferring the load from the highly compressed part of the 0° plies to the highly in-tension part of the 0° plies.

3.7. Head Position Study

3.7.1. Results

Figure 3-20 shows the σ_1 distributions around the holes of joints equipped with HS or DAN bolts in both cases of run-out heads and of plate-interior heads. Figure 3-21 summarises the maximum values reached by all stress components in each configuration (the most stressed plies may change between the configurations).

CHAPTER 3. STRESS DISTRIBUTION AROUND THE HOLES OF SINGLE-LAP COMPOSITE BOLTED JOINTS UNDER TENSILE LOADING

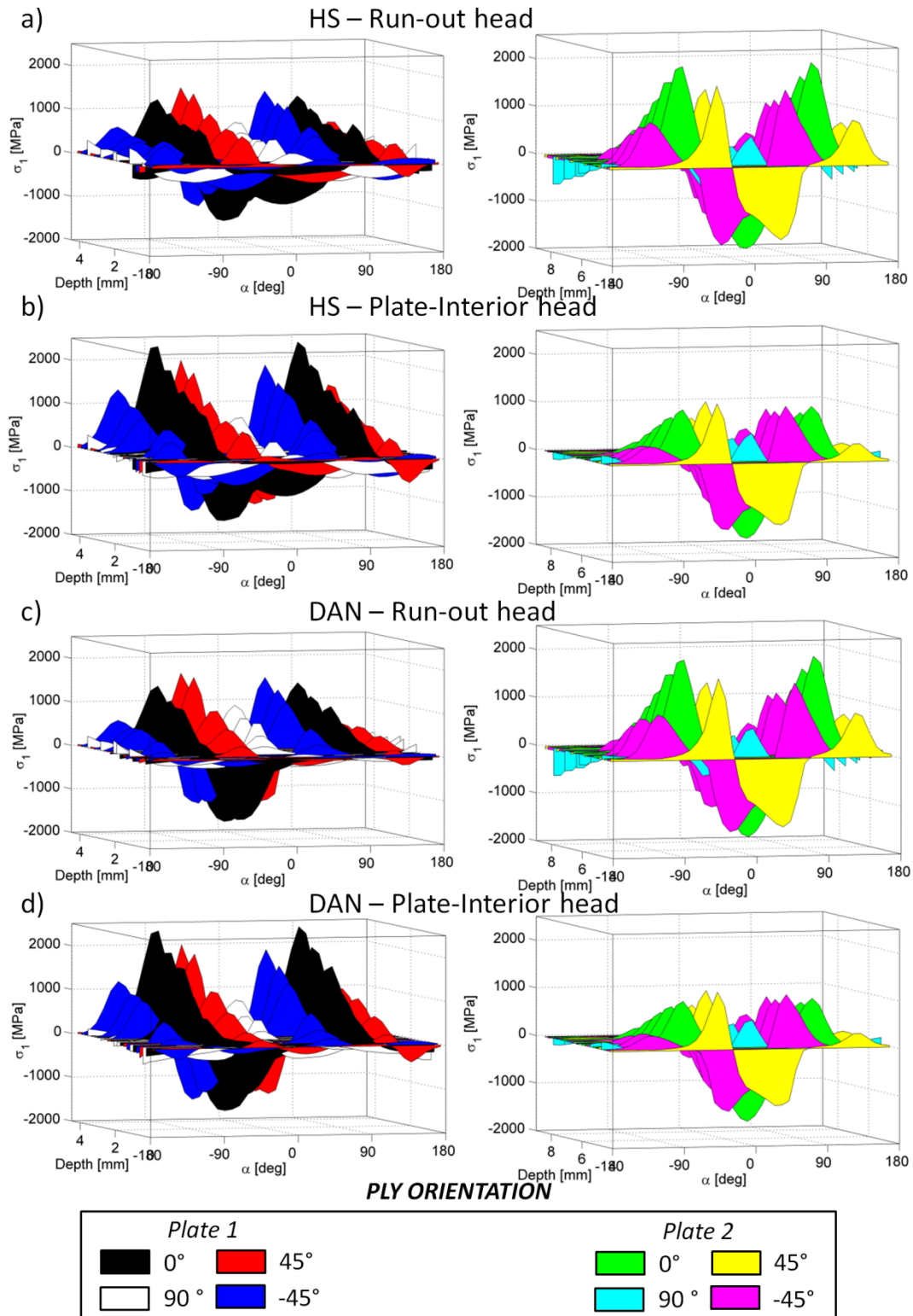


Figure 3-20. Distributions of σ_1 around the holes of joints (under tension loading) with different bolt positions and different bolt head heights. (Plate 1 – plate with countersink hole, Plate 2 – plate with straight hole)

Changing the position of the bolt head does not appear to change the main features of the σ_1 distribution, but affects greatly the maximum values reached, especially in tension. Independently from the bolt used, in plate 1 the maximum tensile σ_1 values reached are greatly increased using plate-interior heads. Even though the increase in the 45° and -45° oriented plies is significant, the highest increase in tension is on the 0° oriented plies, resulting to be the plies with the highest stress of plate 1. Moving from run-out heads to plate-interior heads has the opposite effect on plate 2: a dramatic decrease of the tensile σ_1 values in the 0° oriented plies and a more limited drop in the 45° and -45° oriented plies, the latter becoming the highest stressed plies in tension in plate 2.

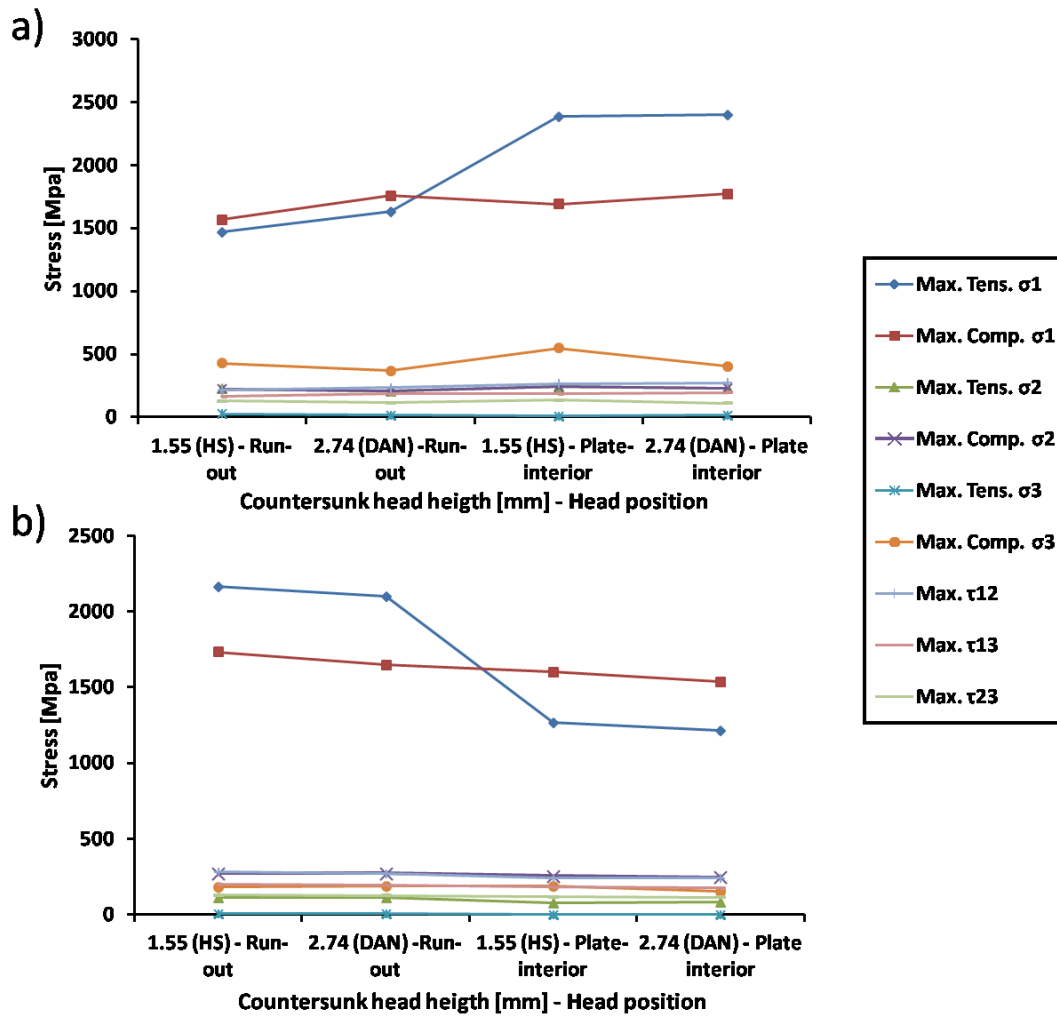


Figure 3-21. Maximum values of the six stress components around the holes of bolted joints with different countersunk head height and head position in the plates. a) Plate 1. b) Plate 2.

The position of the countersunk head affects only weakly the compressive σ_1 values around the holes of the two plates. When passing from configurations with run-out heads to ones with plate-internal heads, regardless of the type of bolts installed, plate 1 exhibits a mild increase in the σ_1 compressive maximum values in the 0° oriented plies and a slightly more pronounced increase in the 45° and -45° oriented plies. In plate 2 the effect is exactly the opposite: a mild decrease in the σ_1 compressive maximum values in the 0° oriented plies and a slightly more pronounced

decrease in the 45° and -45° oriented plies. On the contrary, the σ_1 distribution in the countersink does not appear to be strongly affected by the position of the head.

Errore. L'origine riferimento non è stata trovata. shows a comparison between the load-displacement curves of the joints equipped with HS or DAN bolts in both cases of run-out heads and of plate-interior heads. These curves are obtained using the FE model presented in the previous chapter. It may be seen that the position of the head does not seem to lead to a noticeable change of stiffness of the joints up to the load considered for the stress analysis.

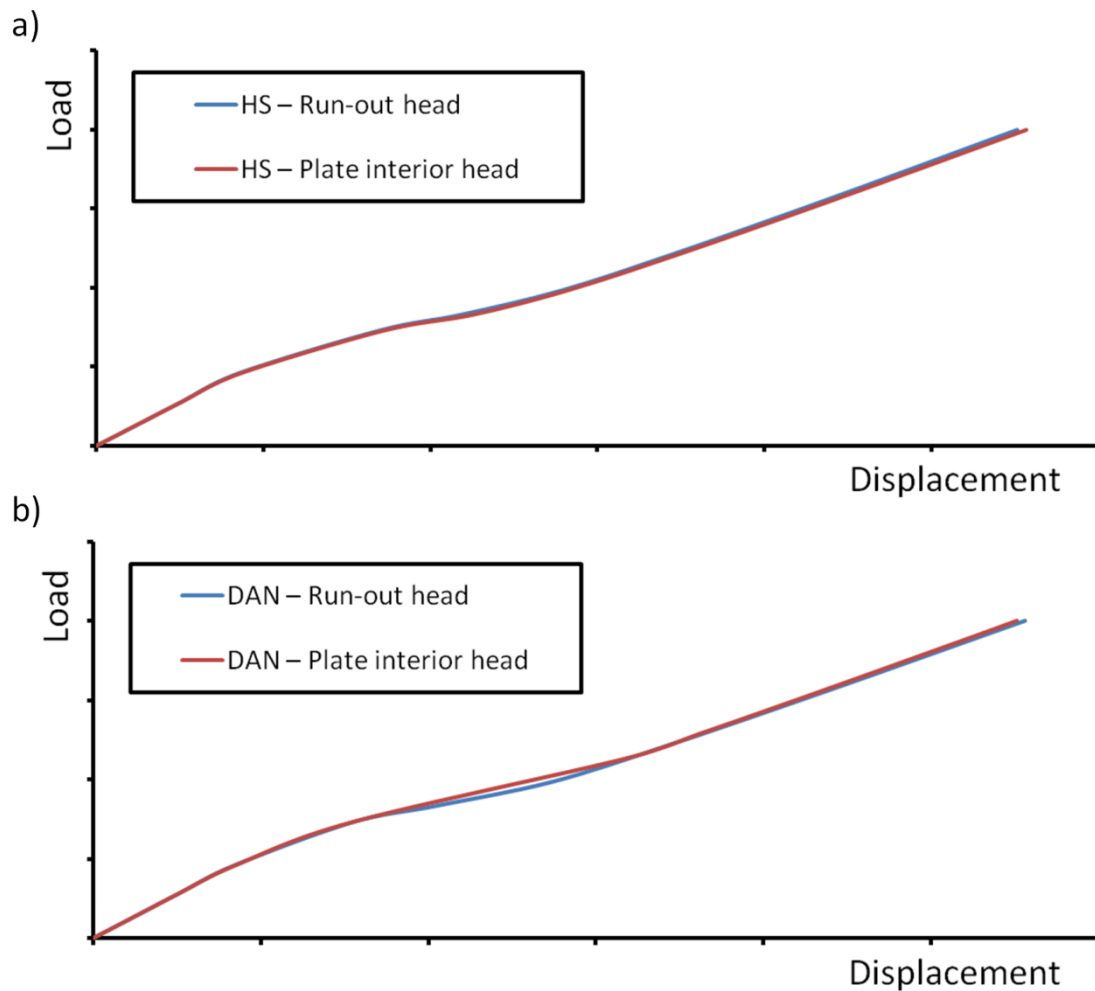


Figure 3-22. Comparison between the load-displacement curves of the joints equipped with HS or DAN bolts in both cases of run-out heads and of plate-interior heads.

3.7.2. Discussion

Due to the anti-symmetry of single lap shear joints, each bolt contributes to transferring roughly 50% of the load applied to the joint, from a plate to the other one. Even if both bolts contribute in the same amount in transferring the load, and the stress state of the two bolts is theoretically identical, the same argument is not valid for the material around the two holes connected to the same bolt. In each plate, the load sustained by its section varies along the length of the plate and mainly depends on the position of the bolts. Figure 3-23 shows the variation of the load sustained by the plate sections along the length of a single lap shear joint. This simplified graph is obtained from the FE analysis and for clarity does not consider the minor effects of the distributed load exchanged through friction between the plates and the in-plane load created in the countersink. Similar investigations have been performed by Andriamampianina et al. [91] and Ekh et al. [21] in case for multi-row joints. The different loads sustained in different sections of a plate affects deeply the stress state of the composite material, especially the tensile σ_1 stress of the 0° oriented plies. These plies have the fibres oriented in the same direction of the load and carry the load along the length of the plate.

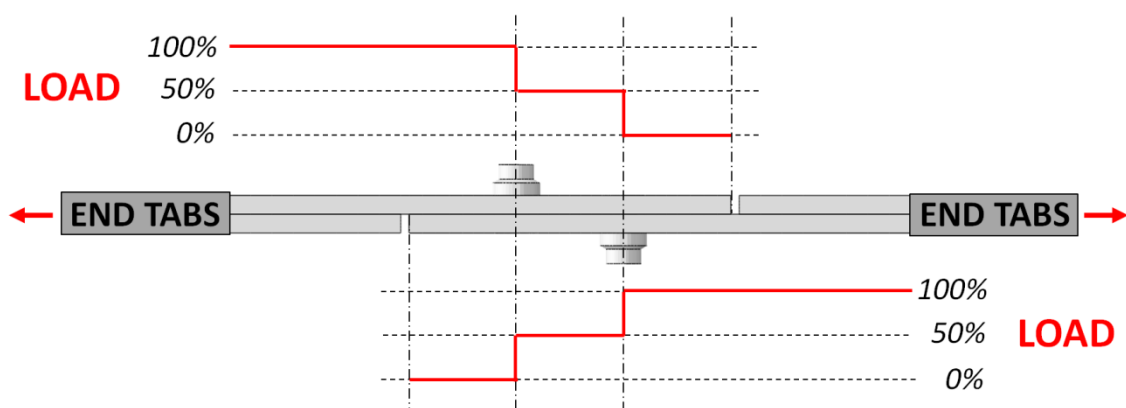


Figure 3-23. Load levels (respect to the load applied to the joint) sustained by the sections of the two plates along their length.

The plate section in the plate-interior position sustains approximately double the load carried in the run-out position. This has the direct effect, when going from a run-out head to a plate-interior head configuration, of roughly doubling the tensile σ_1 maximum values in the 0° oriented plies, at an angle α of 90° and -90° , in plate 1. The opposite is valid for plate 2 where, going from a run-out head to a plate-interior head configuration, the tensile σ_1 maximum values in the 0° oriented plies is halved. This highlights that the maximum tensile σ_1 values in the 0° oriented plies are directly dependent on the load carried by the section of the plate where the bolt is installed, which is affected by the relative positions of the bolts in the joint.

The maximum tensile σ_1 values in the 45° and -45° oriented plies are also affected by the load carried by the plate section, but to a minor extent. In plate 1, at an angle α of -45° and 45° respectively, σ_1 increases when passing from a run-out head to a plate-interior head configuration. The opposite is true for plate 2. As seen in the previous sections, the 45° and -45° oriented plies have the role of deviating the load around the hole and transfer it to the 0° oriented plies. This applies to the load locally transferred by each bolt, which is not influenced by the bolt position, and to the load already sustained by the plate section, which needs to be deviated to pass around the geometrical discontinuity formed by the hole. The position of the head is of greater importance for the secondary compressive σ_1 peaks at an angle α of 135° and -135° . Here, the 45° and -45° oriented plies have the role of redistributing the load into the plate section after having passed the hole. Since the load in the section of plate 1 doubles when passing from a run-out head to a plate-interior head configuration, the maximum tensile σ_1 values in those secondary peaks doubles as well. The opposite is valid for plate 2.

The position of the head in the joint has also a small effect on the maximum compressive σ_1 values. In the 0° , 45° and -45° oriented plies, passing from a run-out head to a plate-interior head configuration has the effect of slightly increasing the maximum compressive σ_1 values in plate 1 and decreasing them, roughly of the same amount, in plate 2. A likely cause for this limited variation is the localised secondary

bending in correspondence of the plate-interior position of each plate (Figure 3-24). This local deformation of the plate appears to lead to slightly higher maximum compressive σ_1 values and to a less homogenous σ_1 distribution between the plies along the plate thickness.

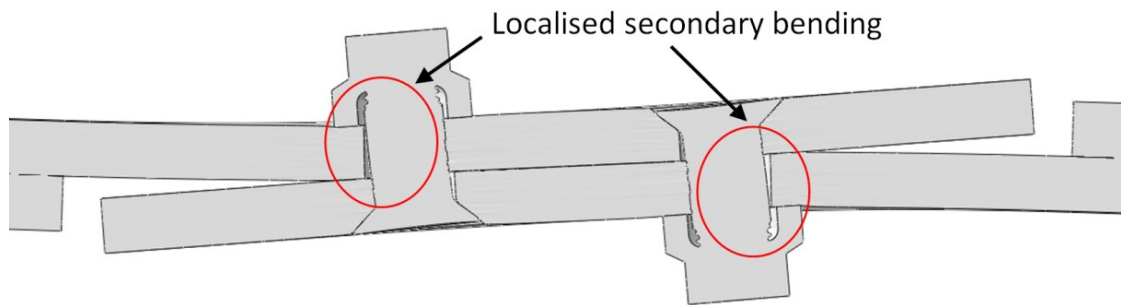


Figure 3-24. Localised secondary bending in the joint which enhances the stress level of the hole in the first plies from the faying surface.

Increasing the height of the head in the plate-interior head configurations appears to have the same effect as for run-out head configurations: in tension, the countersink acts as a geometric discontinuity creating stress concentrations. In compression it reduces the cylindrical part of the hole decreasing the number of 0° oriented plies carrying the load.

It is well known that the cracks that lead to a net-section failure start at about an angle $\alpha=90^\circ$ and -90° [6] and that, in case of a single-lap joints with two bolts, this failure develops at the plate-interior hole [89]. The net-section failure takes place at the plate-interior hole rather than at the run-out position because, the section corresponding to the plate-interior hole sustains a load roughly doubled with respect to the section corresponding to the run-out hole. In the σ_1 distribution, as already discussed, the only plies at an angle $\alpha=90^\circ$ and -90° with a high level of stress are the 0° oriented plies and their maximum σ_1 value are directly proportional to the load sustained by that plate section. This highlights a direct link between ply failure and joint failure, with the tensile fibre failure of the 0° oriented plies at the edges of the hole triggering the net-section joint failure.

Since the joint failure mode is deeply influenced by the joint geometric ratios (such e/d and w/d) and by the stacking sequence of the plates, it is not possible, for this type of joint, to indicate either the run-out or the plate-interior position as the best head position for every possible configuration. As previously discussed, the countersink creates a concentration of stress in the plates and, therefore, increases the stress level determined by the load and bolt position. For this reason, in a joint configuration prone to net-section failure, the countersunk head should be placed in the run-out position, while for configurations prone to shear-out failure the head should be placed in the plate-interior position.

3.8. Conclusions

This chapter has presented a finite element analysis of the stress distribution around the holes of single-lap CFRP joints, with two countersunk bolts, under tensile loading. The distributions of the six stress components have been analysed in detail in a reference joint and the effects of head height, shank-hole clearance and position of bolt heads have been investigated through parametric studies.

The proposed method is based on the FE bolted joint model with a high-level of detail shown in the previous chapter, extracting the stress values from the first ring of elements around the two holes connected to the same bolt. The data are arranged in 3D plots, showing the stress distribution in each ply of the two plates.

The analysis of the reference joint shows that almost all stress components strongly increase when approaching the faying surface. The presence of the countersink is clearly visible but its local effect on the stress level remains limited. The σ_1 distribution forms a clear pattern of spaced peaks (depending on the ply fibre orientations), both in tension and compression, σ_2 and σ_3 are mainly in compression (due to the clamping force) and τ_{12} , τ_{23} and τ_{13} does not appear to follow a clear pattern. σ_1 is identified as the most critical stress component for bearing and the

compressive part of its distribution is largely determined by the extent of the shank-hole contact. In agreement with the literature, the compressive fibre failure of the 0° oriented plies, at the centre of the contact, is identified as the initiation of the bearing damage micro-mechanism.

Increasing the countersunk head height, and therefore the dimensions of the countersink, causes a reduction of the material around the hole and leads to concentrations of stresses. Only the 0° oriented plies in the cylindrical part of the hole are found to sustain the bearing load. Therefore, increasing the head height leads to fewer plies involved, to higher σ_1 in these plies and could decrease the joint bearing strength. Although having a less high countersunk head may be beneficial for bearing, this could lead to a lower joint tensile strength due to a premature fastener failure.

A higher clearance leads to a reduction of the extent of the shank-hole contact and, therefore, to higher contact pressure and compressive σ_1 and to a reduction of the joint stiffness. This higher stress would cause an initially higher level of damage, but, according to the literature, would have only a limited effect on the joint bearing strength. This could be caused by the damaged surface of the hole, accommodating the bolt and behaving as if the bolt-hole clearance was effectively reduced. 45° and -45° oriented plies are found to have the role of transferring the load from the compressed fibres of the 0° oriented plies, in contact with the bolt, to the in-tension fibres of the 0° oriented plies, at the sides of the holes. Due to this role, they are found, in the literature, to be crucial in determining the joint bearing strength and the occurrence of the shear-out joint failure.

In a single lap joint, the load sustained by the plate varies along its length and mainly depends on the position of the bolts. The plate section corresponding to the bolt next to the run-out sustains about 50% of the load applied, while the plate section corresponding to the bolt towards the interior of the plate, carries about 100% of the load. The tensile σ_1 maximum values in the 0° oriented plies exhibit a direct dependency on the load sustained by the plate section, which doubles from one

position to the other. For this reason, the net-section failure occurs always at the hole towards the interior of the plate. In addition, the 45° and -45° oriented plies exhibit a dependency on the load sustained by the plate section but to a minor extent. The compressive σ_1 distribution, instead, does not appear to be significantly affected by the position of the bolt.

3.9. Publications

It is envisaged that the contents of this chapter will be submitted for journal publication in the near future.

Chapter 4

Experimental fatigue investigation of the mechanical behaviour of composite bolted joints with real-time monitoring of clamping force and bolt crack initiation

4.1. Introduction

In the aeronautical industry, a vast variety of composite bolted joints are currently used. These can differ for several parameters, such as type and number of bolts, plate number, materials, bolt clamping force used, dimensions, etc. Even though each of these parameters may have a great impact on the fatigue performance of the joint, running an experimental fatigue characterisation on each possible joint configuration may be unfeasible and economically inefficient. For this reason, it is,

instead, more efficient to investigate in detail the joint fatigue mechanical behaviour and understand how this is affected by the main joint parameters.

This chapter presents fatigue experimental tests on composite bolted joints with the use of a novel method to monitor in real-time the loss of clamping force and detect crack initiation and propagation in the countersunk fasteners. The method uses strain gauges and an algorithm to process the data and is validated experimentally. The chapter describes and discusses experimental results obtained testing joints with different thicknesses and countersunk bolt heads. The variation of the clamping force during the fatigue test is investigated, as well as the interaction between the bolts during the failure process. A connection between static and fatigue test results is highlighted and the joint failure sequence in fatigue is described.

4.2. Methodology

4.2.1. Method outline and specimen setup

The method proposed to monitor the bolt clamping force uses the readings of the external load applied to the joint specimen (Figure 4-1) (from the machine's load cell), the data from a strain gauge located close to each bolt and an algorithm to post-process the data.



Figure 4-1. Specimen of a composite bolted joint for the fatigue single lap shear test.

Each strain gauge is located next to a bolt nut (Figure 4-2 and Figure 4-3) and is orientated perpendicularly to the main direction of the specimen. Two forces are applied to the specimen:

- Clamping force of the bolts, which deforms locally the plates around the fasteners, applied during the assembly of the joint;
- Cyclic external load, applied during the fatigue tests.

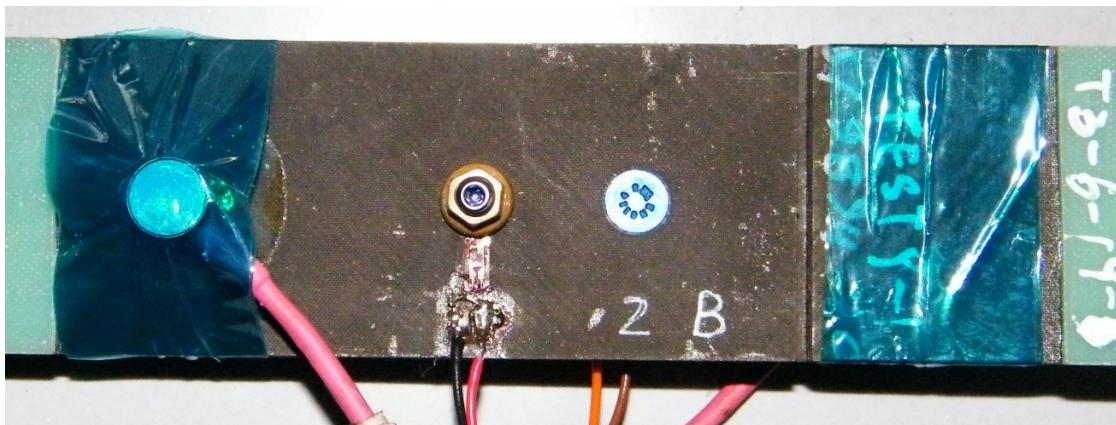


Figure 4-2. Specimen equipped with 2 strain gauges (and acoustic emission sensors not used in the presented method).

During the fatigue test, because of their particular position, the strain gauges read the changes in strain caused by both the applied external fatigue load and loss of

clamping forces. Assuming that the recorded strain has an almost-linear response to the clamping force and to the external load, it is possible to apply the superposition principle. In this way, the total strain recorded is simply the sum of the strains related to the two forces.

To have clear readings of the strain related to the clamping force, it is necessary to subtract the strain caused by the cyclic external load. This is possible if the location and the orientation of the strain gauges are properly selected and the strain is filtered using a suitable algorithm.

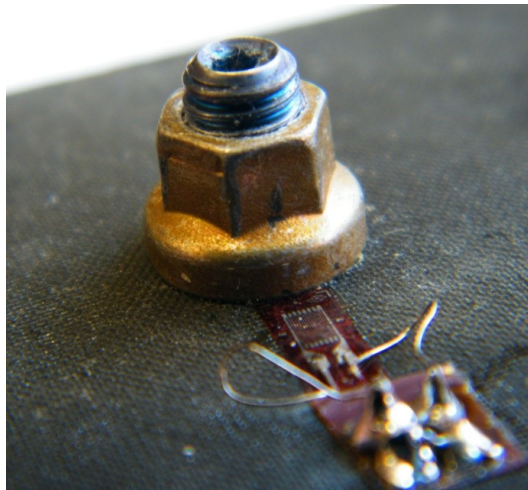


Figure 4-3. Location of the strain gauge.

4.2.2. Selection of the strain gauge location and orientation

The particular location and orientation of the strain gauges (Figure 4-2 and Figure 4-3) has been selected (1) to be sufficiently sensitive to detect the change in strain related to the local deformation of the plates due to the loss of bolt clamping force and (2) to reduce the effect of the external cyclic load on the readings. The location and the orientation of the unidirectional strain gauges have been selected using the numerical model of a composite bolted joint described in Chapter 2, with the

same shape and dimensions of the specimens tested in fatigue. In Figure 4-4, it is possible to see the model's mesh with the 8 nodes considered as possible locations for the strain gauges. Figure 4-5 shows the strain in the radial direction for the 8 nodes during the phases of (i) Clamping force application, (ii) Initial ramp-up of the external load on the joint and the (iii) Ramp Down and (iv) Ramp up of the fatigue load cycle. Location 7 has been chosen because of the relatively high strain caused by the clamping force, the relatively stable response of the joint during the initial ramp up (non-linearity caused by the friction and the slipping of the plates described in Chapter 2) and the limited variation of strain during the ramp up and ramp down compared to the strain caused by the clamping force. The numerical results confirm the validity of the assumptions highlighting the linearity of the strain vs. the clamping force and the external load during the fatigue cycle and the degree of superposition of the effects.

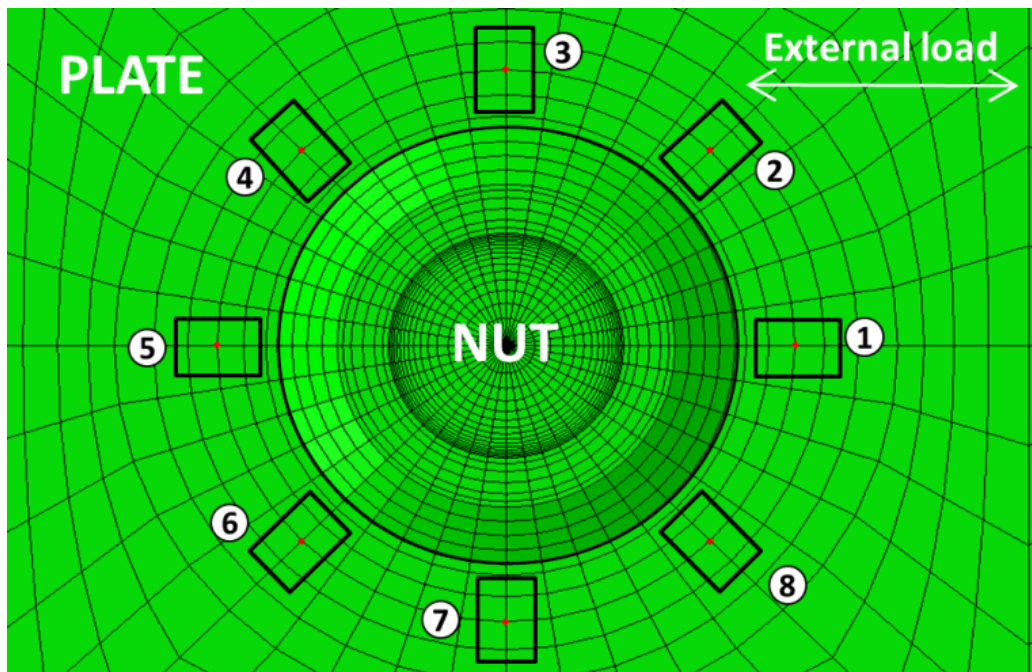


Figure 4-4. Eight positions analysed as possible locations for the strain gauge.

4.2.3. Data processing algorithm

The data from the strain gauges and from the load cell is recorded simultaneously in order to know the level of external load applied to the specimen for every strain reading. The sampling frequency needs to be significantly higher than the frequency of the applied load and, in particular, high enough to study the variation of the strain during the load cycle. In general, the higher the recording frequency, the more effective the algorithm will be in filtering the strain related to the cycling external load.

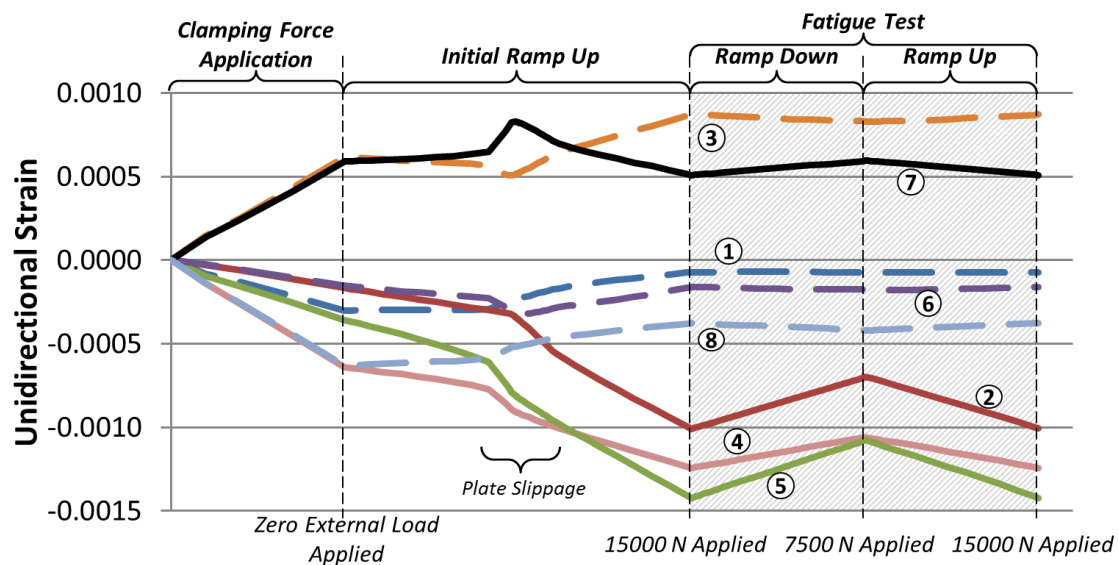


Figure 4-5. Strain during the several phases of the test in the eight considered locations.

The proposed algorithm to detect the loss of clamping force during fatigue tests is divided into six steps:

1. The algorithm recognises the load cycles in the data, identifying the position and values of the maximum and minimum loads for each cycle through the use of the two load thresholds. The maximum load is defined as the maximum value found above the top threshold and the minimum load as the minimum load found below the bottom threshold. When the

load passes, first, through the top and, then, through the bottom threshold, the recorded maximum load is saved and a new collection is started. The opposite concept is used to identify the minimum load.

2. The entire data collection is divided into half-cycle sets delimited by the identified maximum and minimum loads. Each half-cycle set represents either the ramp up or the ramp down of a load cycles.
3. For every half-cycle set, a linear regression is run using the method of the least squares to obtain the best fit of the strain vs. external load data. The equation of the best fit line is then used to extrapolate the value of the strain related to a zero external load (Figure 4-6), which is the strain caused only by the clamping force. A decrease in this strain thus indicates that the bolts are losing clamping force. For every cycle two values of zero-load strain are produced from the code: the first is related to the extrapolation from the ramp up set of the cycle and the second is related to the ramp down set. The difference between these values is a good indicator to assess at every moment of the test the amount of non-linearity in the readings and therefore the validity of applying the superposition principle.
4. To calibrate the method, it is necessary to record and use as references the strain gauges readings after the joint failure (strain corresponding to zero clamping force). Another suitable way to calibrate the method, having a more quantitative evaluation but using a more complicated set-up, is to apply the strain gauges before the bolt tightening and record the strain before and after the clamping force is applied.
5. A Clamping Force Index (*CFI*) is calculated for each cycle, both for the ramp up and the ramp down, for each bolt. The Clamping Force Index for the cycle *i* is defined as:

$$CFI_i = \frac{\varepsilon_i - \varepsilon_{fin}}{|\varepsilon_{ini} - \varepsilon_{fin}|};$$

where ε_i is the extrapolated strain for the i -th cycle (either for the ramp up or the ramp down), ε_{ini} the extrapolated strain found at the first cycle of the test and ε_{fin} is the strain used as reference for a zero clamping force applied.

6. A graph for each bolt is produced showing the values of the Clamping Force Indexes (both from the ramp up and the ramp down sets) vs. the cycles.

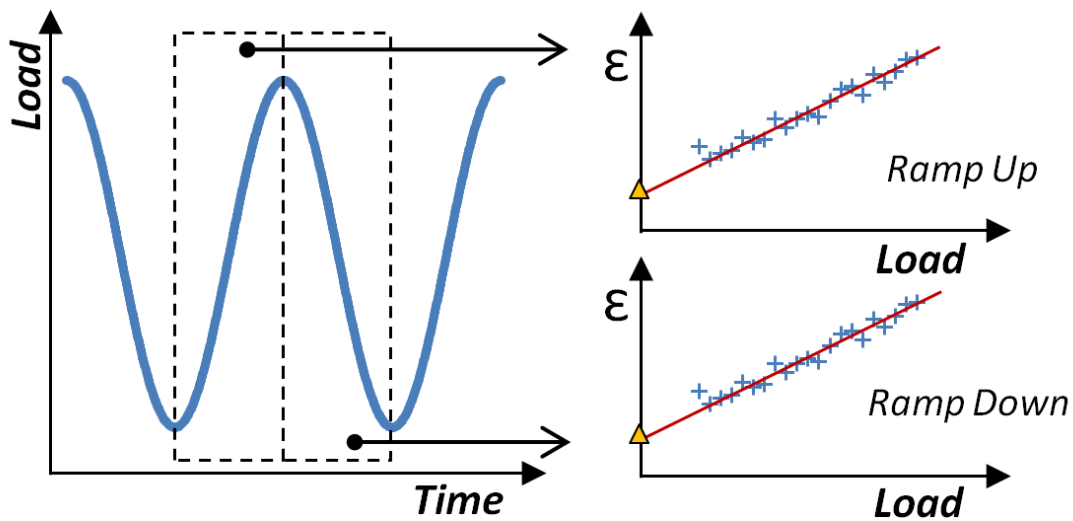


Figure 4-6. Extrapolation of the strain associated to a zero external load applied.

This method can be applied to every type of cyclic load and without the need of knowing the R ratio, the maximum and minimum loads or the load frequency. The shape of the load-time graph does not have to be sinusoidal but can be any periodic function. Maximum and minimum loads and frequencies can be changed throughout the test, making the method suitable to be used in fatigue tests with complex load spectra.

4.2.4. Real time implementation

A real-time implementation of this method has been created to have readings of the CFI and extrapolated strain directly during the tests. Obtaining this information

CHAPTER 4. EXPERIMENTAL FATIGUE INVESTIGATION OF THE MECHANICAL BEHAVIOUR OF COMPOSITE BOLTED JOINTS WITH REAL-TIME MONITORING OF CLAMPING FORCE AND BOLT CRACK INITIATION

allows the software to stop the test when a certain criterion is reached. Subsequently the user can inspect the level of damage developed until that point in the composite plates and bolts. In this way it is possible to correlate the level of damage in bolts and plates with the CFI readings and with the number of cycles and fatigue load applied.

The real-time implementation has been developed in LabVIEW (Figure 4-7) and is composed of the following modules:

- **Control.** This module creates a sin wave signal to guide the opening of the servo valve controlling the movement of the tensile machine head. The maximum and minimum values of the wave are constantly adjusted through a proportional control feedback loop to match the desired load conditions.
- **Recording.** This module continuously records the values of load, displacement of the machine head and strain read by the two strain gauges.
- **Real-time linear regression and calculation of the CFI.** This module continuously collects data, recognises cycles and executes real-time linear regressions of the data to extrapolate the strain associated only with the bolt clamping force.
- **Automatic test stop.** The software stops the generation of the sine wave and interrupts the test when a certain criterion is satisfied. Several criteria can be used such as the use of a threshold on the CFI or on the displacement or the detection of a sudden drop of these two values. The criterion that has proven to be most successful in stopping the test at the onset of fast damage development is the use of a floating threshold on the extrapolated strain. This is defined as an offset from a continuously updated average of the extrapolated strains from a group of previous cycles.

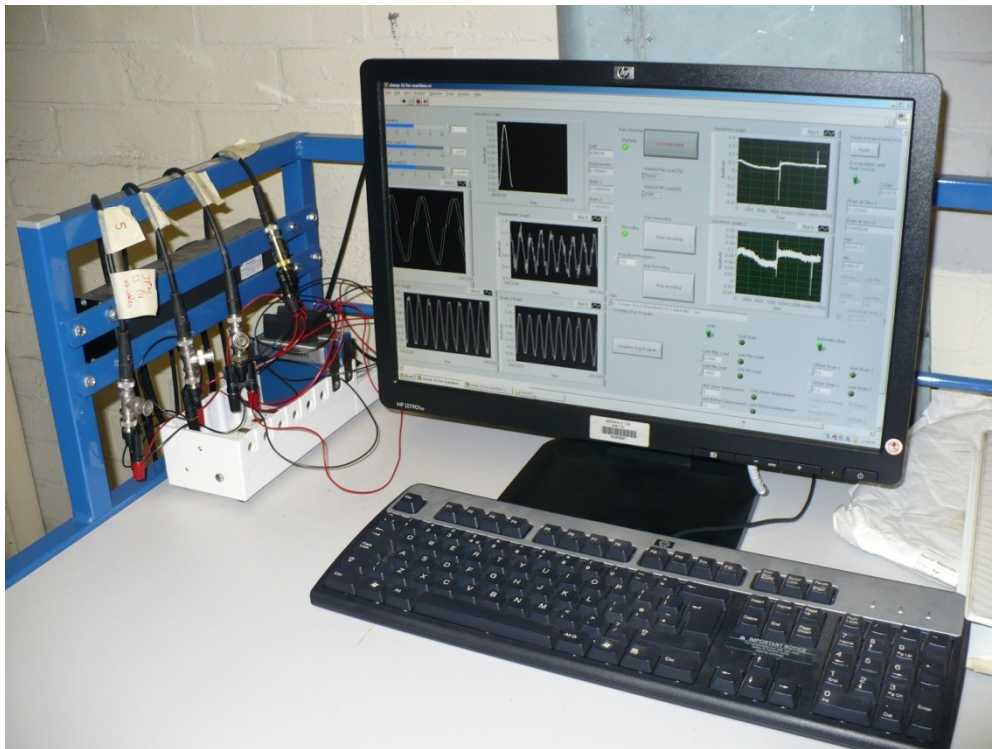


Figure 4-7. Real-time implementation of the method to monitor clamping force and detect bolt crack initiation during fatigue tests of bolted joints. Implementation developed with LabVIEW.

4.3. Joint behaviour during fatigue tests

4.3.1. Results

The presented method has been tested on single lap composite bolted joints under fatigue testing. The R ratio used was 0.1 and the frequency 7 Hz. Here the results of one test are presented to show the joint behaviour during a fatigue test. This test was run until final failure. The joint final failure consisted of fastener failure with cracks at the head root of both bolts and of limited damage in the composite plates.

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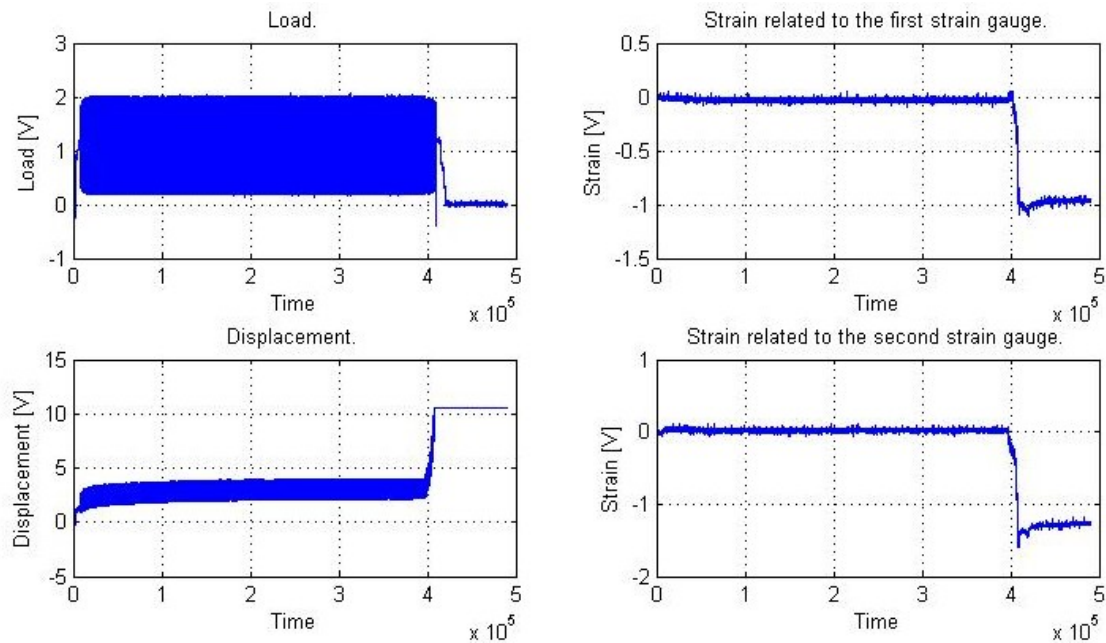


Figure 4-8. Raw data recorded during the fatigue test: load and displacement from the machine sensors and two strain readings from the strain gauges located next to the nuts.

Figure 4-8 shows the raw data obtained from one of these fatigue tests:

- Load, which oscillates between a minimum and a maximum value until the joint final failure;
- Displacement, which also oscillates following the load and increases slowly throughout the test until a sudden increase, associated with a fast damage propagation;
- Strain associated with the first bolt, which oscillates with an almost constant form for most of the test with a strong decrease close to the end of the test;
- Strain associated with the second bolt, similar to the previous one.

Processing the data using the proposed algorithm, it has been possible to obtain the graph of the Clamping Force Index of the two bolts during the fatigue test. Figure 4-9 shows that the entire test lasted for 10,046 cycles, with the clamping forces of the

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two bolts having almost constant values for most of the test. From about 300 cycles before the final joint failure, the clamping forces seems to drop and to keep decreasing until final failure, caused by fastener failure.

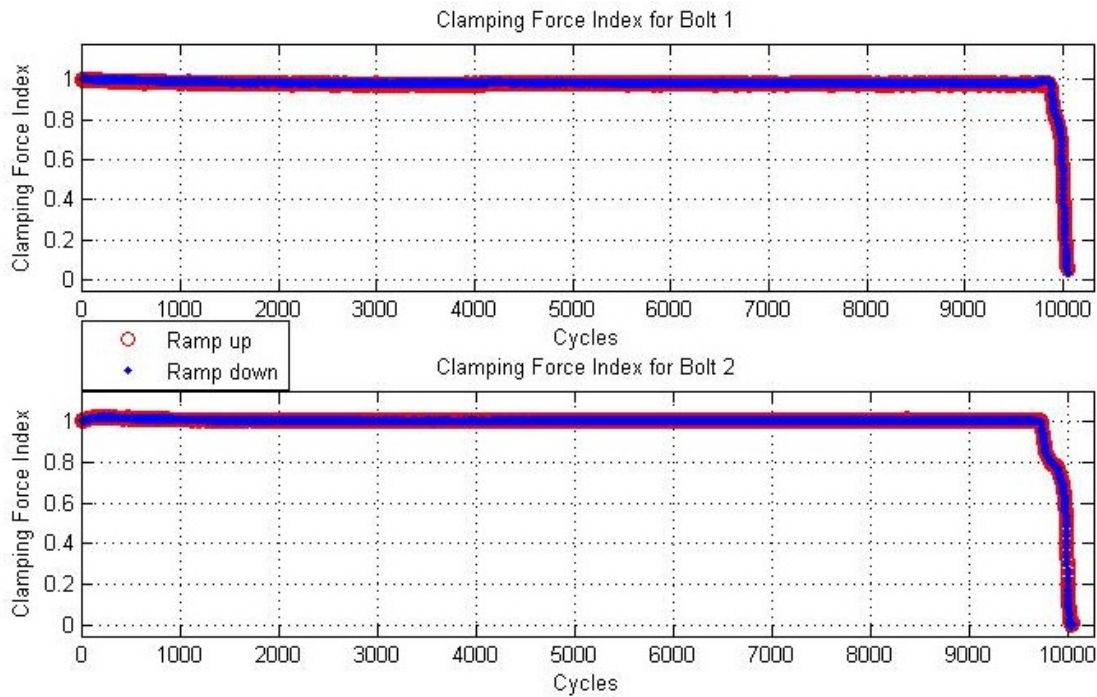


Figure 4-9. Result of the method - Clamping Force Index in the two bolts throughout the cycles.

Regarding the validity of the superposition principle assumed, in Figure 4-9 it is possible to see, in different colours and symbols, the values of the Clamping Force Indexes obtained analysing the data of the ramp up and ramp down of each cycle. The two sets of values are very similar, especially in the first part of the test. After the clamping force drops, the difference between the two sets is at the highest of the entire test; this is likely to be caused by the damage developed in the bolts or in the plates, which add non-linearity to the strain response.

4.3.2. Discussion

Figure 4-9 shows that the values of the Clamping Force Index are almost constant for most of the test. The drops in the *CFI* near the end of the test suggests a relatively quick damage propagation. The damage initiation stage seems to last for an important fraction of the entire joint fatigue life. This fatigue behaviour would allow the joint to have a reliable mechanical response for most of its fatigue life, with an unchanged bolt clamping force and a constant joint stiffness, but would also lead to a possible fast damage development which could be difficult to detect before the final failure.

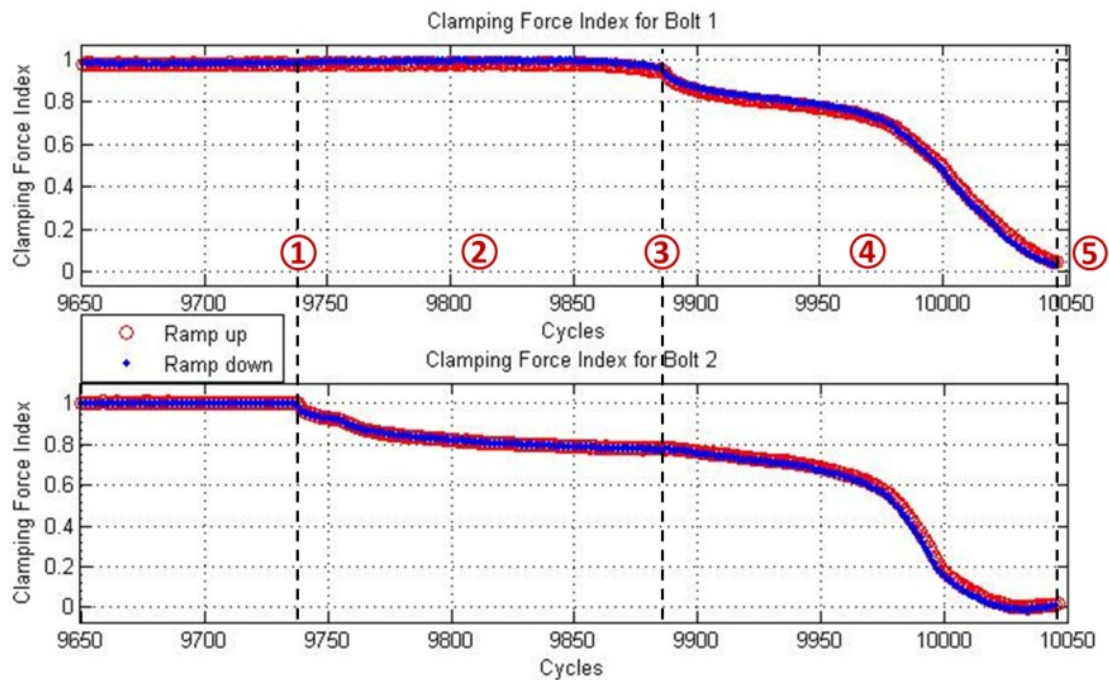


Figure 4-10. Detail of the failure process of the two bolts – (1) 2nd bolt crack initiation, (2) transfer of load and crack propagation deceleration, (3) 1st bolt crack initiation and increased velocity of the crack in the 2nd bolt, (4) crack propagation velocity of both bolts increased and fast but stable fatigue crack propagation, (5) final failure.

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In Figure 4-10 a detail of the Clamping Force Index vs. cycles graph during the last part of the test is shown. It is possible to identify a sequence of events leading to the joint final failure:

1. Sudden drop of *CFI* in the second bolt. This is likely to be correlated to a crack initiation in the bolt head root (location of the final failure);
2. Slightly increased reading of *CFI* in the first bolt and slower loss of *CFI* and reduced damage propagation rate in the second bolt. The damage in the second bolt leads to a change in the distribution of load between the two bolts: part of the load, which was carried by the second bolt, now more compliant because of the damage, is transferred to the first bolt. The load transfer causes an apparent increased reading of the *CFI* of the first bolt. The fact that this increases so slightly indicates that the method proposed is effective in screening out the effect of the external cyclic load. The decreased load carried by the second bolt causes the damage propagation rate to strongly decrease. The global effect is the transfer of load between the bolts with the protection of the damaged bolt by the undamaged one.
3. Sudden drop of *CFI* in the first bolt. This is likely due to a crack initiation in the head root of the first bolt. This causes a more even redistribution of the load carried out by the two bolts and an increase of the crack propagation rate in the second bolt. This is confirmed by the *CFI* readings: at the instant when the crack initiates in the first bolt, it is possible to observe a change of the shape in the *CFI* vs. cycles curve of the second bolt.
4. Both fasteners are failing and the crack propagation rates increase progressively. The shapes of the curves in the two bolts are initially different but, with the developing of the damage and with additional load transfers, rapidly become similar. The fatigue crack propagation in the last phase is fast but stable; since in the graphs every point represents the reading of an entire cycle, it is possible to notice that the last phase of the

failure process is characterised with a high but almost constant crack propagation rate. This phase lasted about 150 cycles in the presented test.

5. Final failure of the joint with fully propagated cracks in both bolt heads. The last point in both graphs represents the *CFI* for the last load cycle that the specimen has been able to complete before final failure. It is possible to note that in the Bolt 2 the *CFI* has already reached a value around zero before the joint final failure. Instead Bolt 1 still retains a little amount of clamping force which is lost statically during the ramp up of the uncompleted last cycle.

4.4. Method validation

In the previous section, the crack initiation in the bolt head root has been indicated as the reason for the sudden drop of *CFI* and recognised as the trigger for the final failure process. To investigate if this hypothesis is correct, to inspect the damage extent, to validate the method and to test the responsiveness of the real-time code, a set of fatigue tests have been launched. These are set to automatically stop when a drop in the extrapolated strain of at least one of the two bolts is detected.

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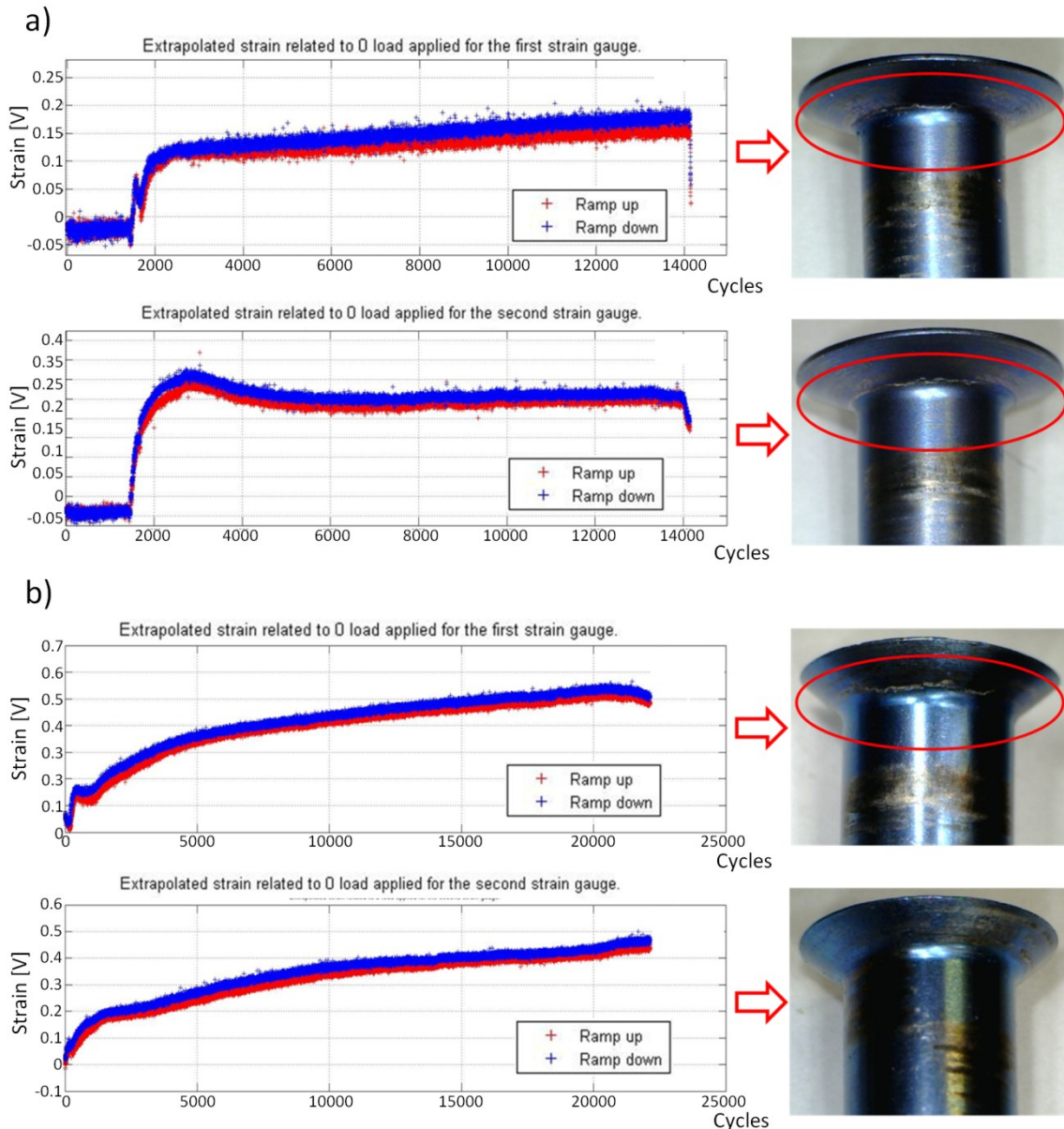


Figure 4-11. Validation of the method. a) The test was stopped when the method detected crack initiation in both bolts. Small cracks found in both bolts. b) The test was stopped when the method detected a crack initiation in the first bolt. A small crack found in the first bolt and none in the second.

Figure 4-11 shows the results of two of these tests automatically stopped. In this case, the graphs record on the y axis the extrapolated strain instead of the CFI since the needed after-final-failure reference strain is not available. It can be noted that, in the graphs, the data before the final failure process appear to have a stronger

variation than in Figure 4-11. This apparent difference is only due to the different vertical scales applied to the graphs: in Figure 4-9 the graphs need to fit also the data related to the final failure process which have a stronger variation in the y direction than the ones presented in Figure 4-11. Figure 4-11a shows a test automatically stopped after more than 14,000 cycles because of a drop detected in the extrapolated strain of both bolts. After the stop, no signs of damage are visible from the exterior of the joint and the displacement readings do not show any appreciable increase. On the contrary, disassembling the joint reveals a small crack at the roots of both bolts and only a limited bearing damage around the composite plate's holes. Figure 4-11b shows a test automatically stopped after more than 22,000 cycles because of a drop detected in the extrapolated strain of bolt 1. Once more no signs of damage are visible from the exterior of the joint. Disassembling the joint reveals a small crack in bolt 1, where the drop in the extrapolated strain was detected, and no cracks in bolt 2, where no drop has been detected yet.

The test results presented in Figure 4-11 demonstrate that the sudden drops in the CFI graphs, detected using the proposed method, are, as hypothesised, caused by crack initiation developed in the bolt head root. The crack initiation appears to cause a loss of stiffness in the bolt heads which reduces suddenly the clamping force. In addition, in the test results reported in Figure 4-11b, even though only one of the bolts of the joint experienced a drop in the extrapolated strain and developed crack initiation, the bearing damage, found around the holes of the composite plates, appears to be of comparable entity around the two bolts. This seems to suggest that the bearing damage plays a limited role during the start of the fatigue final failure.

The real-time implementation of the method seems responsive enough, not only to detect a bolt crack initiation and stop the test before final failure, but also to stop the test in between of the crack initiations of the two bolts.

4.5. Fatigue tests of joints with different heads and thickness

4.5.1. Test Matrix

The proposed method has been applied to the fatigue tests of composite bolted joints with different bolt heads and thickness ($R=0.1$, frequency=7Hz) (Figure 4-12). The aim of these tests is to have a first assessment of the performance of the investigated joint configurations in terms of cycles to fatigue failure and cycles to crack initiation. The tested joint configurations (Table 4-1) comprise two different thicknesses and 4 different bolt heads (Figure 4-13). The main joint dimensions and characteristics, in common to all configurations, are shown in Figure 4-14.

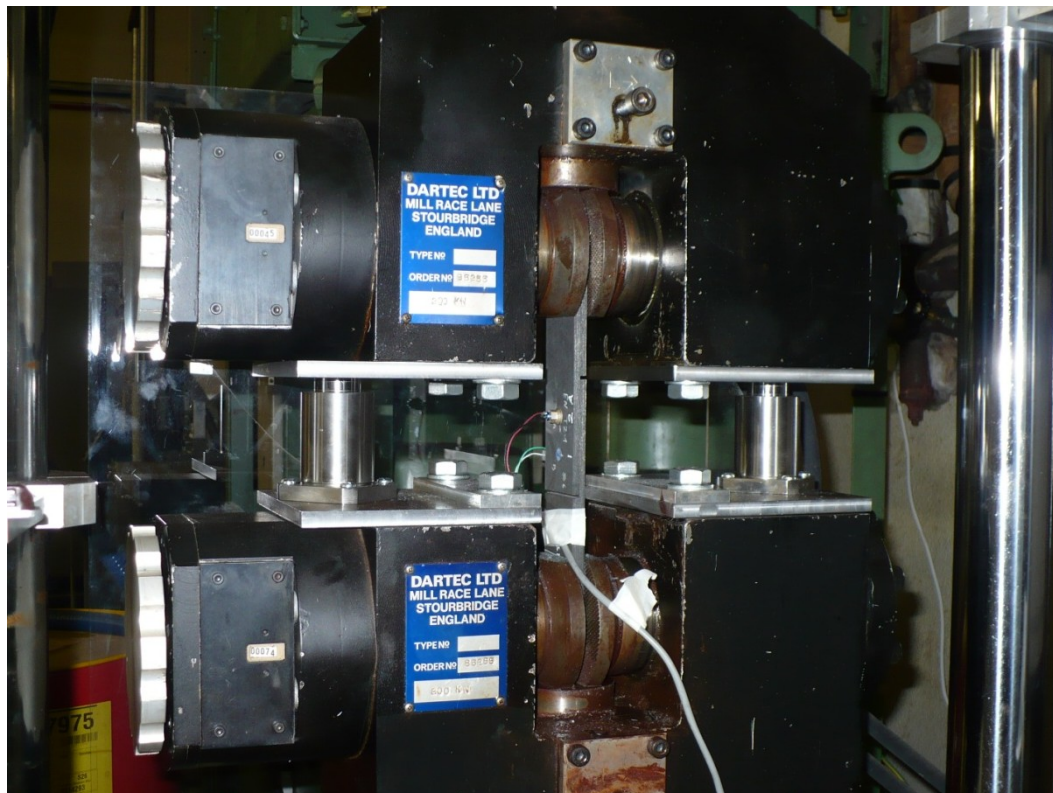


Figure 4-12. Experimental setup for the fatigue tests ($R=0.1$) of single-lap composite bolted joints.

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Table 4-1. Joint configurations tested in fatigue

<i>Configuration Name</i>	<i>Bolt type</i>	<i>Bolt Diameter [mm] (d)</i>	<i>Head height [mm] (h)</i>	<i>Head angle [deg] (θ)</i>	<i>Plate thickness [mm] (t)</i>	<i>t / d</i>	<i>h / t</i>
ABS t2	ABS	6.35	1.55	130°	4.416	≈ 0.7	0.35
HS t2	HS	6.35	1.55	100°	4.416	≈ 0.7	0.35
EN t2	EN	6.35	1.88	100°	4.416	≈ 0.7	0.43
DAN t2	DAN	6.35	2.74	100°	4.416	≈ 0.7	0.62
ABS t1	ABS	6.35	1.55	130°	2.994	≈ 0.5	0.52
HS t1	HS	6.35	1.55	100°	2.994	≈ 0.5	0.52
EN t1	EN	6.35	1.88	100°	2.994	≈ 0.5	0.63
DAN t1	DAN	6.35	2.74	100°	2.994	≈ 0.5	0.91

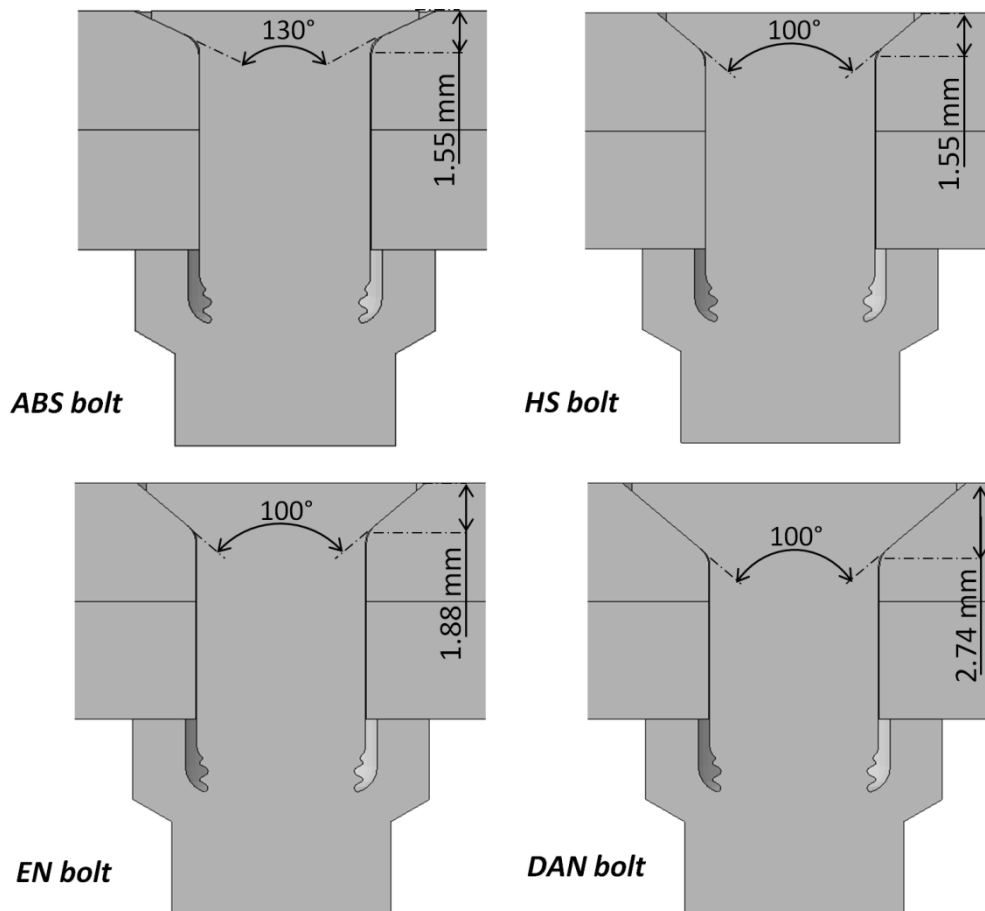


Figure 4-13. Bolt heads used in the fatigue tests (only the configurations with 4.416 mm plates are shown in the figure).

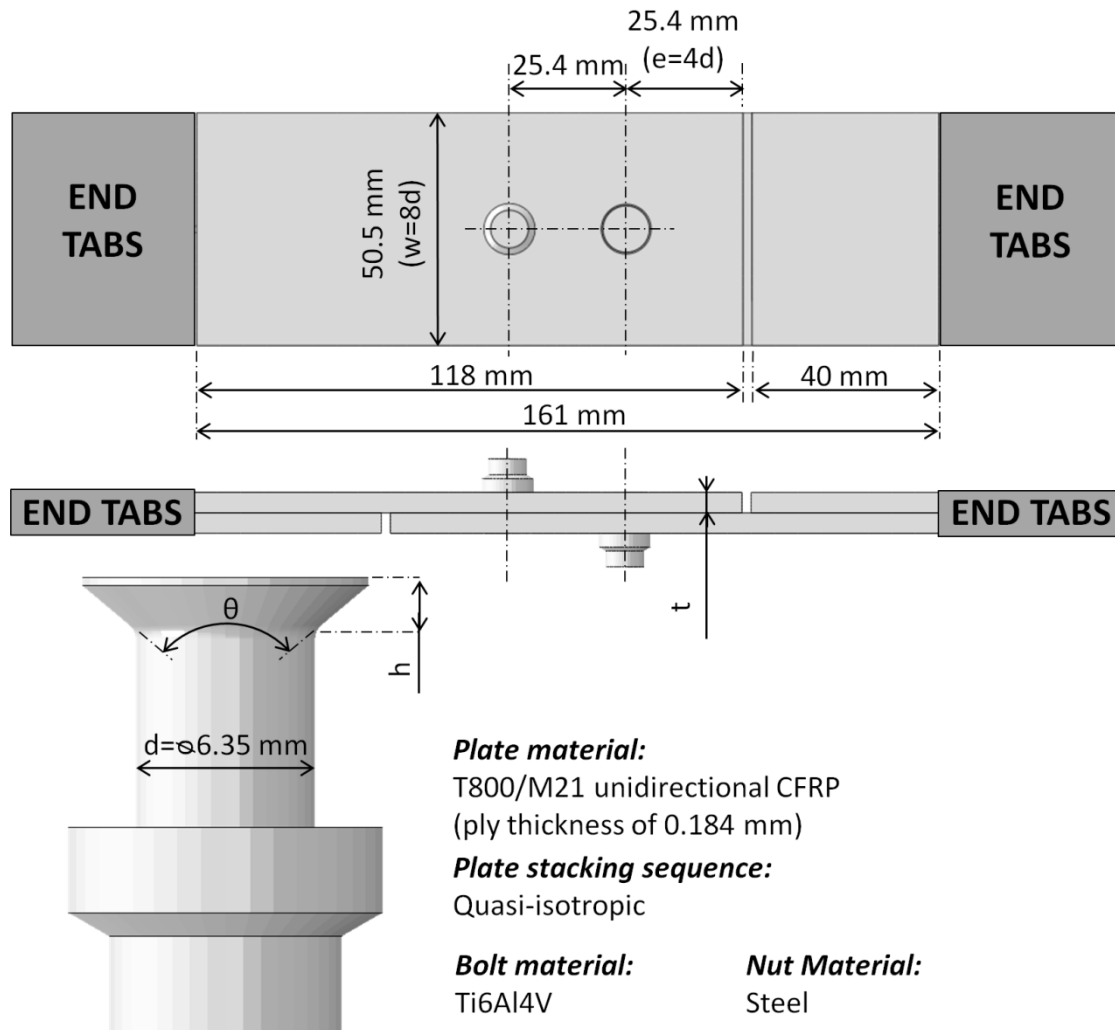


Figure 4-14. Common dimensions and properties to all joint configurations tested in fatigue.

4.5.2. Results

Figure 4-15 shows the results of all the fatigue tests performed. On the y axis of the S-N graph is indicated the maximum value of the cyclic load applied, on the x axis the number of cycles. Every joint configuration is associated with two versions of the same symbol, one filled and one hollow. The former indicates the cycle at which final failure occurred and the latter the cycle at which crack initiation has been detected.

The tests that reached a number of cycles around a million were stopped (indicated in Figure 4-15 with an arrow) and the fatigue life of these joints considered infinite when the respective cyclic loads are applied. Some joint test results report a crack initiation cycle but no cycle corresponding to the final failure: these are the tests automatically stopped to validate the method and to investigate the damage in plates and bolts before final failure.

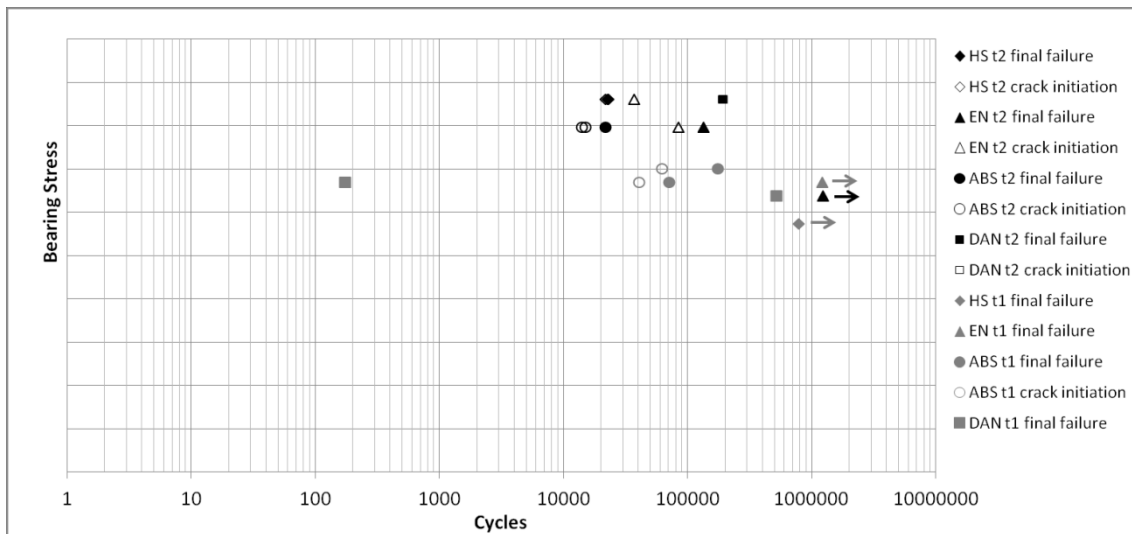


Figure 4-15. Fatigue results for all tested joint configurations, in terms of both cycles to crack initiation and to final failure.

4.5.3. Discussion

4.5.3.1. Joint performances

Despite the limited amount of data available to evaluate the variety of the presented joint configurations, a few observation can be noted. In Figure 4-15, the results associated with the specimens with thicker plates occupy a generally higher portion of the S-N graph than the results of the joints with thinner plates. Therefore, the joints with plate thickness of 4.416 mm ($0.7 t/d$) appear to have better fatigue performance than the joints with 2.994 mm plates ($0.5 t/d$). This was found also by Mínguel et al. [69] in case of aluminium plates.

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Figure 4-16 shows a close-up view on the fatigue results of the joints with 4.416 mm plates. For this plate thickness, the joints with the best performance result (even if the data are too scarce to lead to a final conclusion) are the ones with DAN bolts, followed by the ones with EN, HS, and then ABS bolts. The joints with DAN, EN and HS bolts were tested at the same cyclic maximum load. The DAN joint lasted for 193,657 cycles, the EN joint initiated a crack around 37,000 cycles and the HS joints initiated a cracks and failed around 23,000 cycles. The ABS joints, despite being tested at a lower load, initiated the cracks around 15,000 cycles and failed around 23,000 cycles.

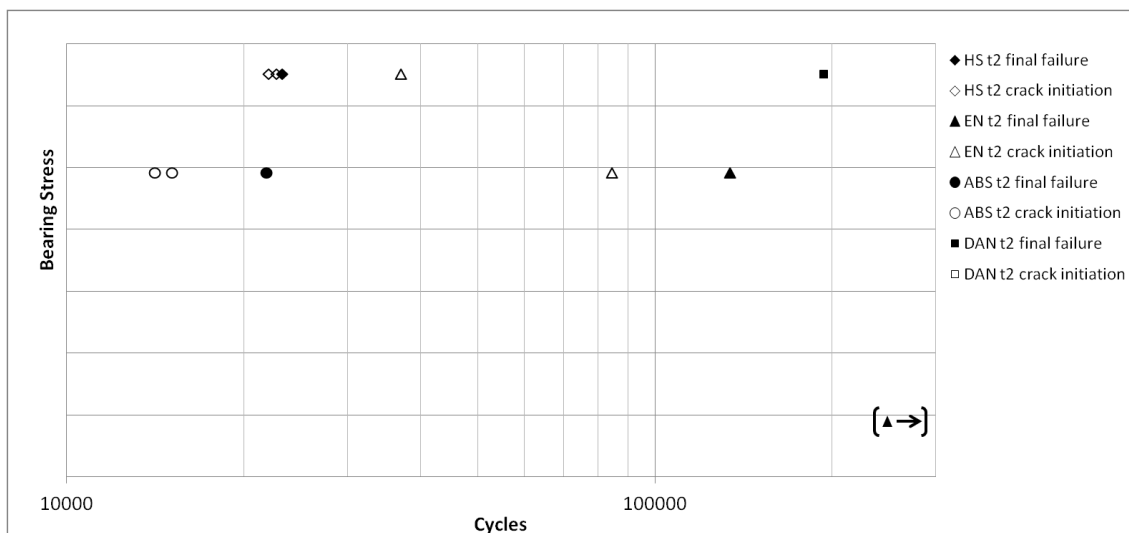


Figure 4-16. Fatigue results for all tested joint configurations with 4.416 mm plates (t2), in terms of both cycles to crack initiation and to final failure.

Figure 4-17 shows a close-up view on the fatigue results of the joints with 2.994 mm plates. For this plate thickness, the ranking of the joints with the best performances is different from the previous case: joints with EN bolts perform in fatigue better than ABS and DAN joints. These joints are fatigue tested at the same maximum load, with the EN joint testing interrupted after more than a million cycles and without any visible crack in heads and nuts, the ABS joint initiating a crack at 40,905 cycles and failing at 71,695 cycles, and the DAN joint failing after only 175 cycles. The test result of the HS joint, instead, does not give any useful information on

the comparison between the joints since this is tested at a lower load and the test is interrupted around 800,000 cycles without any detection of crack initiation.

The reason for the strong difference in performance of the joints with DAN bolts will be discussed in section 4.7.2.

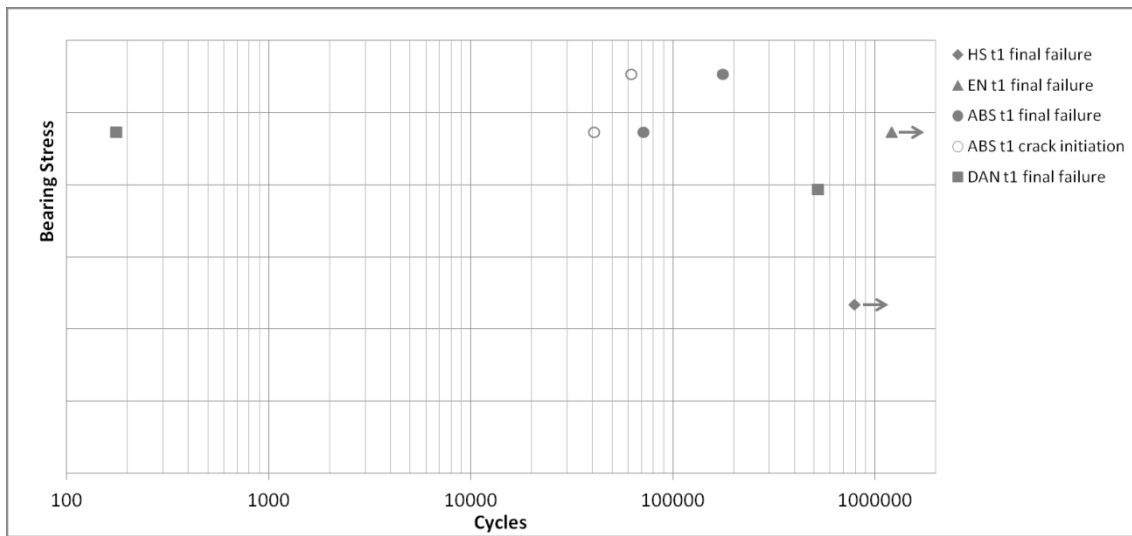


Figure 4-17. Fatigue results for all tested joint configurations with 2.994 mm plates (t1), in terms of both cycles to crack initiation and to final failure.

4.5.3.2. Repeatability of crack initiation

In Figure 4-16, two joints with HS bolts and two joints with ABS bolts were tested respectively at the same cyclic load. The aim was to investigate, in a test, the damage in the joint after crack initiation, interrupting automatically the test, and, in the remaining test, to study the joint until final failure. For both joints with HS and ABS bolts, the crack initiations of the two tests have been detected with a good approximation around the same number of cycle. This highlights that the crack initiation of the bolts shows a good repeatability for the same joint configuration and cyclic load applied.

4.5.3.3. Fastener failure

The final failure of all the tested joints has coincided with the complete propagation of cracks in bolts. For all the joints with HS and ABS bolts (relatively small heads), the cracks are located at the countersunk head root (Figure 4-18b). On the contrary, for all the joints with DAN bolts (much bigger heads), the cracks are found at the first thread (Figure 4-18a). In the tested joints with EN bolts (intermediate heads), the final failure has corresponded to either cracks in heads or at the first thread.

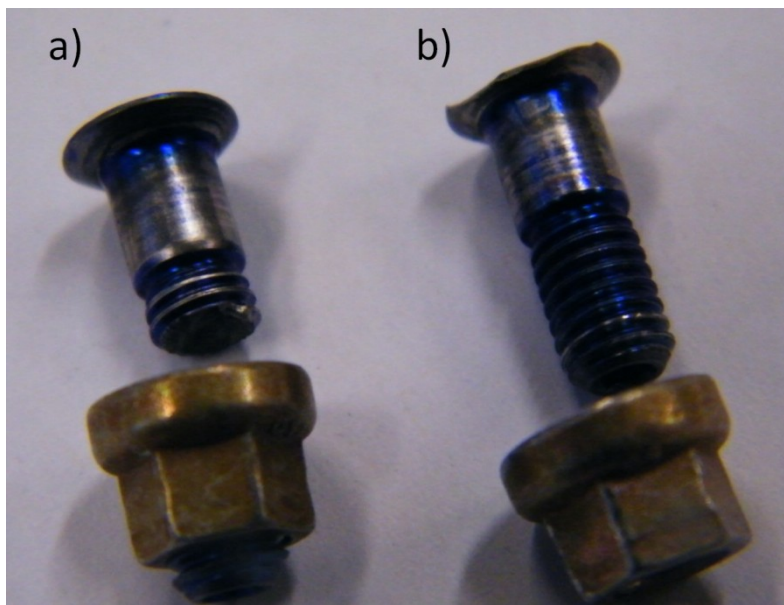


Figure 4-18. a) Fastener failure with a crack at the first thread (joined with the nut). b) Fastener failure with a crack in the head.

The method developed has been found able of monitoring the clamping force and the CFI in bolts and detect their reduction caused by the crack initiation in the heads, but, on the contrary, does not appear to detect any gradual reduction caused by first thread cracks. A likely reason for this is that cracks of relatively small dimensions in the first thread would not lead to a substantial change of stiffness in the bolts and therefore to a loss of clamping force. In this way, when the fatigue crack in the first thread has grown enough to fail statically, the clamping force and CFI, as observed, drop in a single cycle from the initial value to zero.

In the joints with final failure caused by cracks in the head, it has not been possible to observe any crack at the first thread. On the contrary, in some joints with first thread failure, it has been possible to observe (and previously detect) an initiated crack in the head. This suggests a possible parallel development of cracks in both head and first thread. Depending on the strength of the head and thread, the crack will initiate in first instance in one of these two locations. In the joints with HS and ABS bolts, the head is relatively small and is seen to be weaker compared to the first thread (all head failures occur in the tested joints). On the contrary, in the DAN joints, the head is much bigger and is found to be stronger than the first thread (all first thread failures occur in the tests). With a medium sized head, the EN joints experienced both cases of head failure and first thread failure, showing a comparable strength of head and first thread. As already discussed, the propagation of cracks in the bolt heads, from initiation to final failure can take a fair portion of the joint fatigue life. Instead the cracks in the first thread seem either to be much faster to propagate (since no traces have been found in joints with cracked head) or not visible to the naked eye until final failure.

4.5.3.4. Undamaged/damaged fatigue life of the joints

Unlike conventional fatigue tests, where only the cycles to final failure are obtained as output, with the presented method it is possible to obtain the number of cycles to crack initiation. In this way, it is possible to introduce the concept of undamaged and damaged fatigue life of the joint (undamaged considering crack initiation as the first major damage in the joint), defined as the number of the fatigue cycles before and after the crack initiation. This information is important for design purposes since the crack initiation, even if it does not change immediately the stiffness of the joints and is not visible from the exterior of the joint, corresponds to a macroscopic change in the structure of the joint. This means that, after the crack is initiated, the joint is damaged and may have different static mechanical properties compared to the undamaged state. Without the indication of the length of the

undamaged life of the joint, it is difficult to estimate for how long a bolted joint can retain the initial static mechanical properties when subject to in-service/fatigue loading. This can lead to a less confident or over-conservative design.

The undamaged to total fatigue life ratio can vary substantially, when changing thickness and bolts installed. From a maximum of 0.947 in a joint with HS bolts and 4.416 mm plates to a minimum of 0.353 in a joint with ABS bolts and 2.994 mm plates. The amount of data available in this investigation does not allow any final conclusion on the effect of plate thickness and bolt head on the undamaged to total fatigue life ratio. Despite this, the repeatability shown by the crack initiation and the demonstrated difference of the ratio between different joint configurations, motivate further and deeper investigations into the matter. The aim would be to develop joints with not only longer fatigue lives but also with longer undamaged fatigue lives.

4.6. Comparison between fatigue and static test results

4.6.1. Static test results

Figure 4-19 and Figure 4-20 show a comparison of the fatigue test results with the static tests results on the same joint configurations, for plate thicknesses of 2.994 and 4.416 mm respectively. The fatigue tests were performed at Imperial College while the static tests by Airbus UK but manufacturing in the same way the specimens. On the vertical axis ($x=1$ cycles) the static results are reported. For each joint configuration a set of three points is added: the first represent the loads at i) the static final failure, ii) bearing peak and iii) bearing start. The bearing peak load and the bearing start load are concepts proposed here to describe the bearing strength in a different way respect to the standard [3]. The bearing peak load is the load at which the stiffness of the joint is equal to the simple average between the stiffness of the joint after the slippage of the

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plates and the stiffness of the joint before the final failure. The bearing start load is the load at which, from the graphs, it is possible to identify the beginning of the loss of joint stiffness related to bearing damage. These values are reported considering two static tests for each joint configuration and averaging the results.

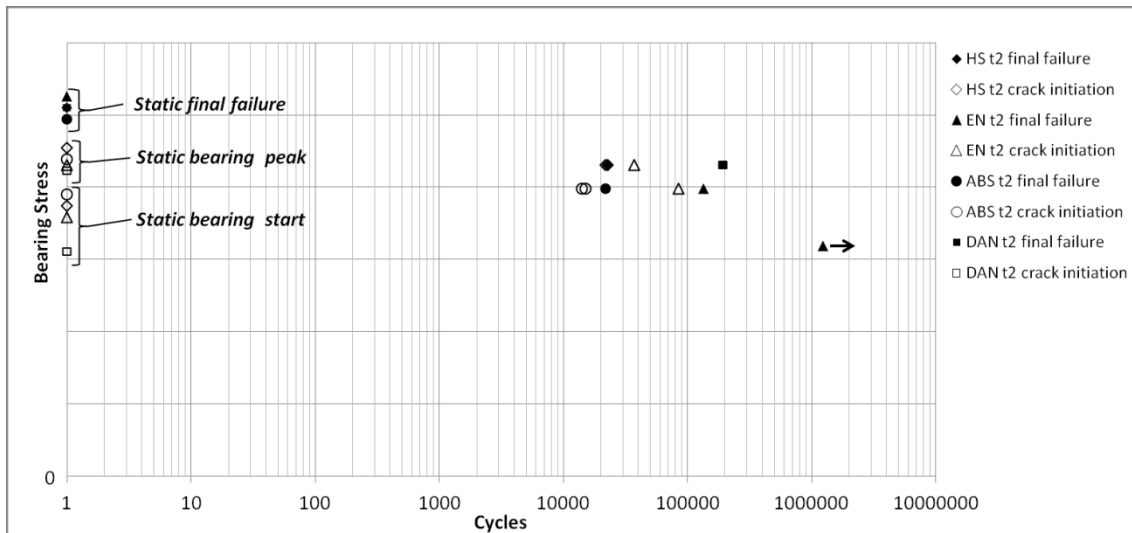


Figure 4-19. Comparison between static and fatigue results for all tested joint configurations with 4.416 mm plates (t2). For each configuration, static and fatigue final failure are shown as well as the static bearing peak start and peak and fatigue crack initiation.

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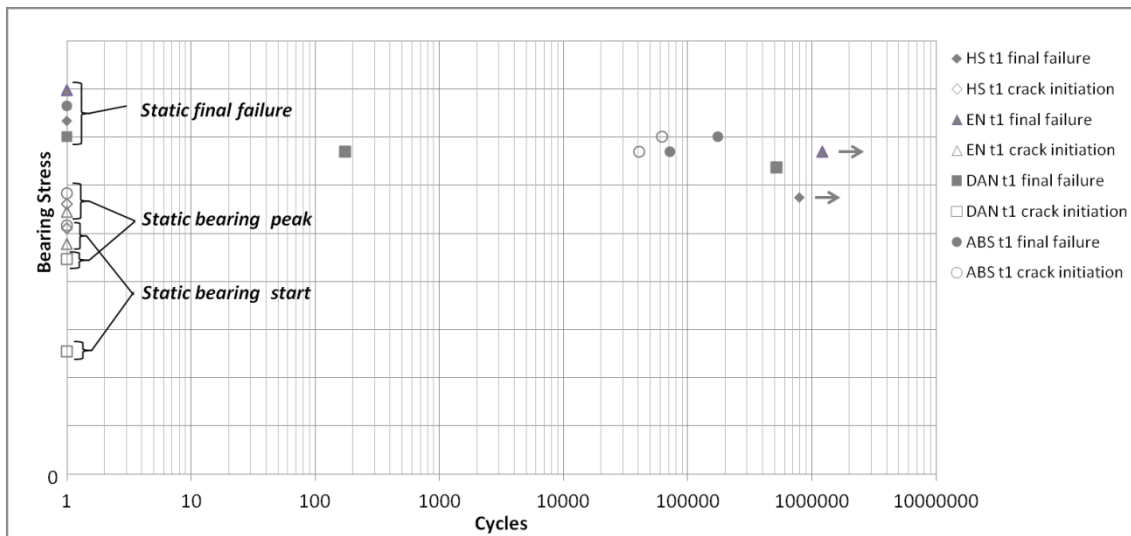


Figure 4-20. Comparison between static and fatigue results for all tested joint configurations with 2.994 mm plates (t1). For each configuration, static and fatigue final failure are shown as well as the static bearing peak start and peak and fatigue crack initiation.

Figure 4-19 and Figure 4-20 show that, for both thicknesses, the joints with both highest bearing peak and bearing start load are the ones with, in order, ABS, HS, EN and DAN bolts (with the sole exception of the HS joint performing slightly better than the ABS joints as bearing peak load with the thickest plates). These correspond to the bolts ordered from the one with the lowest head to the one with the highest head. This highlights the importance for bearing of the cylindrical part of the hole in a plate with a countersink. This importance was already noted in Chapter 3, using a FE model, where the 0° oriented plies of the cylindrical part of the hole were found to be the ones responsible for sustaining the bearing load. Therefore, increasing the height of the countersunk head increases the strength of the bolt but may reduce the bearing strength of the plate. Even though the ABS and HS bolts share the same head height, these show a limited difference in the bearing results. This is the case since the ABS bolts feature a larger head angle (130° instead than 100°) which seems to have an impact on the bearing strength.

4.6.2. Comparison

Figure 4-19 and Figure 4-20 show how all the fatigue results obtained are particularly close, as maximum load and shear stress applied, to the static final failure loads, even at high number of cycles. When lower cyclic loads were chosen, the specimens did not show fatigue failure before 1 million cycles and the tests were stopped. This is particularly the case for specimens with 2.994 mm plates, where a line connecting the static final failure results to the fatigue ones would result almost horizontal. With this plate thickness, the joint with EN bolts passes from a static failure (1 cycles) to a fatigue life considered infinite (no failure after 1,213,580 cycles) with a maximum load variation of 16%. This means that a reduction of only 16% of the load applied may shift the test results from a static failure to an infinite life of the joint. This highlights the strong dependency of the fatigue results from the static performance for this kind of joint, particularly if thin plates are used.

Figure 4-19 and Figure 4-20 shows how all fatigue failures, for both thickness, are obtained at maximum loads higher than the bearing start loads, and, in case of the thinner joints, even at higher loads than the bearing peak load. Therefore, for the studied thicknesses, it has not been possible to obtain fatigue failure at maximum loads lower than either the bearing start or bearing peak load. This seems to suggest the importance of the static bearing damage on the fatigue performance of joints within this range of plate thicknesses and t/d . In addition, it can be stated that, an amount of static bearing damage was present in all joints directly from the first cycle of each test and, therefore, this had some kind of effect on the joint mechanical responses during the fatigue tests.

Figure 4-19 and Figure 4-20 shows that the performances of the joint configurations follow roughly the same trend in static testing as well as in fatigue. For the specimens with a plate thickness of 4.416 mm, the joint with the highest static final failure load is the one with EN bolts, followed by, in order, the ones with DAN, HS and ABS bolts. In fatigue the joint with the best performance is the one with DAN bolts,

followed by the ones with EN, HS and ABS bolts. For a plate thickness of 2.994 mm, the highest static performances are achieved by the joint with EN bolts followed by the joints with ABS, HS and DAN bolts. For fatigue by joints with, in order, EN, ABS and DAN bolts (no relevant data is available in fatigue for the HS joint). While, with a plate thickness of 4.416 mm, the joint with DAN bolts shows high strength, its performance dramatically drops using thinner plates, for both static and fatigue testing. This is likely due to the small cylindrical portion left in the countersink hole using 2.994 mm plates (0.2 mm on 2.994 mm plates versus 1.676 on the 4.416 mm plates) which affects strongly the bearing strength. Figure 4-20 shows that, with the thinner plates, the DAN joint starts to develop bearing damage at a much lower loads respect to the other configurations. This damage reduces the stiffness of the hole-shank connection and allows a bigger rotation of the bolt inside the holes, increasing greatly the stress in head root and first thread. For this reason, a stronger bolt like the DAN may fail at lower loads than theoretically weaker bolts. This argument is valid in static as well as in fatigue since, as already discussed, bearing damage is present in the specimens from the start of each fatigue test. The similarities in the ranking of the joints highlight the strong connection between static and fatigue performance and, in particular, that the factors (such as bolt height and plate thickness) that affect the joint static performance have a similar effect on the fatigue performance.

4.7. Joint fatigue failure mechanism

As outcome of the investigations performed in this chapter, a fatigue failure mechanism for composite bolted joints is proposed. This is applicable for joints failing, statically as well as in fatigue, with a combination of bearing damage and fastener failure.

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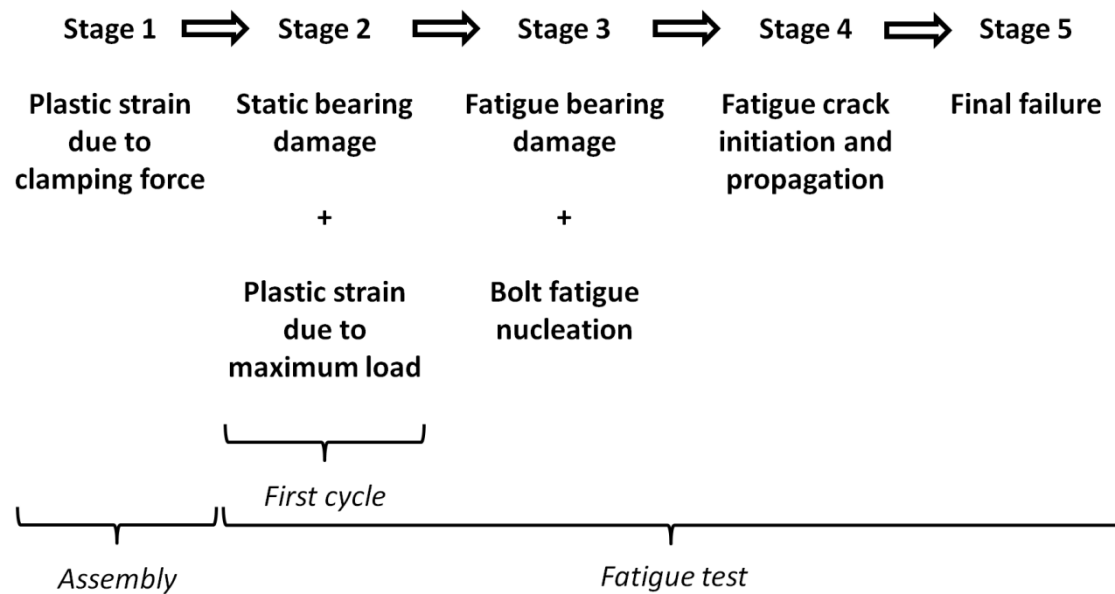


Figure 4-21. Proposed joint fatigue failure mechanism.

The proposed joint fatigue failure mechanism (Figure 4-21) consists of five stages (one during the assembly and four during the fatigue test):

1. Plastic strain development in the bolts during the joint assembly due to the clamping force. The clamping force applied to the bolts during the joint assembly introduces stress in the bolts as well as in the plates. Typically stress concentrations are found in the bolt head root and in its thread. If the clamping force is high enough, the stress in these locations reaches the yield stress and plastic strain develops even before the start of the fatigue test (as observed in section Chapter 2).
2. Static bearing damage in the composite plates and plastic strain growth in the bolts, during the first cycle of the fatigue test. Since the first cycle of a fatigue test is comparable to an loading-unloading static test (or other combinations of loading conditions, depending by the R used), the mechanical behaviour of the joint during the first cycle corresponds to its static behaviour as long as the same loading conditions are applied. In Chapter 2, the five stages of the joint static behaviour have been

presented. After the slippage of the plates and the contact between bolt shanks and plates' holes taking place, if the maximum load is high enough, static bearing damage develops at the hole edges of the composite plates (which is the case for all tested joints in fatigue presented here). In this case the connection shank-hole becomes more compliant, a bigger rotation of the bolts inside the holes is allowed and the bolt head root and first thread become more stressed. This damage is present from the first cycle of the fatigue test and influences the mechanical behaviour of the joint in all following cycles.

The maximum load, during the first cycle, increases the stress state of the bolt caused by the clamping force, or, instead, increases the plastic strain where the yield stress has been already reached (as shown in Chapter 2).

3. Fatigue bearing damage (observed to be small) and bolt fatigue nucleation.

From the second cycle of the fatigue test and until crack initiation, the joint mechanical behaviour does not seem to be subject to strong changes. The test results show that during this stage the clamping force and CFI seem to keep an almost constant value. In addition, the maximum displacements reached by the joints increase only very slightly over time. This seems to suggest that the impact that the fatigue bearing damage (bearing damage created after the first cycle) has on the mechanical behaviour of the joint could be limited in the tested joints with respect to the importance of the static bearing damage. In addition, the test results seems to suggest that the amount of fatigue bearing damage created during the test is limited: in the tested joint with EN bolt and thinner plates, the maximum load applied (Figure 4-20) is well above both the bearing start and peak loads and, despite this, no crack initiation or excessive hole elongation occurred even after 1,200,000 cycles. While the applied cyclic load has resulted not high enough to cause crack initiation in the bolts, this should have been enough to cause fatigue bearing damage since the same load was found to create a

considerable amount of static bearing damage during the first cycle of the test. Even if the fatigue load was high enough to justify the development of fatigue bearing damage, this did not lead to any excessive hole elongation after more than 1,200,00 cycles. This appears to suggest that the development of fatigue bearing damage has been limited during the test and that this had a much smaller effect on the joint behaviour than the static bearing damage. It has to be noted that, a much more relevant fatigue bearing damage development, along with the consequent hole elongation, might occur if lower clamping forces are used (or clamping force is lost over time due to material relaxation) and in case of more severe R ratios, such as $R=-1$.

Since the bolts are subject to cyclic loading, micro-cracks form and grow in the head root and first thread until they reach a critical size, triggering a crack initiation. To be noted that, even if the fatigue tests are performed at a given R, the actual maximum on minimum ratio of the cyclic stress applied to the bolt is deeply influenced by the pre-stress and plastic strain introduced by the clamping force.

4. Bolt crack initiation and propagation. A crack initiates either at the bolt head root or at the first thread. If this occurs at the head root, it causes, as observed, a sudden reduction of the bolt stiffness and a drop of clamping force and CFI of the bolt. This leads to a reduction of the friction between the plates and increases the load transferred through the bolt-hole connection. The crack propagates during the fatigue cycles reducing gradually clamping force and CFI, as well as the joint stiffness and allowing increasing rotations of the bolt inside the holes. This additional rotation has the effect of increasing the bearing damage in the composite plates. Differently from the head crack initiation, when a crack initiates in the first thread, no drop of clamping force and CFI occurs. This is likely due to the fact that a fatigue crack of small dimensions in the first thread does not

change the stiffness of the bolt. Therefore, in case of crack initiation only in the first thread, the joint is not subject to the loss of clamping force, CFI and stiffness until the last cycle of the test, when final failure occurs.

5. Final failure. During the ramp-up of the last cycle of the fatigue test, the crack in the bolt has propagated enough that the fastener fails statically under the maximum load applied. This is associated with a sudden loss of stiffness of the bolt as well as of the joint and, in most of the cases, to the physical separation of the two plates. This separation often causes extensive damage to the composite plates due to the pull-through of the bolts from the holes.

4.8. Conclusions

This chapter has presented fatigue experimental tests on composite bolted joints with the use of a novel method to monitor in real-time the loss of clamping force and detect crack initiation and propagation in the countersunk fasteners.

The method requires the load readings from the machine load cell, the data from a strain gauge located close to each bolt and an algorithm which has been developed to post-process the data. The method assumes the linearity of the strain with the clamping force and with the external load, and the superposition of the two effects. The correct location and orientation of the strain gauges has been chosen using a detailed FE model. The algorithm developed to post process the results divides the raw data in half-cycle sets and runs an extrapolation on each of them to find the strain correlated with a zero external applied load, which is the strain related only to the clamping force. The proposed method could be used with any periodic load cycle and with different maximum loads, R ratios and load frequencies during the test, making it suitable to be applied to fatigue tests with complex load spectra.

CHAPTER 4. EXPERIMENTAL FATIGUE INVESTIGATION OF THE MECHANICAL BEHAVIOUR OF COMPOSITE BOLTED JOINTS WITH REAL-TIME MONITORING OF CLAMPING FORCE AND BOLT CRACK INITIATION

The novel method has been validated experimentally and used to investigate the fatigue mechanical behaviour of the tested joints. An almost constant value of the extrapolated strain (i.e. therefore of the clamping force) is shown for a relevant portion of the joint fatigue life, followed by a decrease in the strain value due to crack initiation and propagation in the bolts. The cycles in which the cracks initiated in each bolt were clearly identified by the algorithm. The results also show the interaction between the bolts during the failure process. When the first bolt starts to fail, part of the load that it carries is transferred to the undamaged bolt, decreasing the rate of change of strain with cycles of the former and reducing its crack propagation rate. During the last cycles, the fatigue cracks propagate in a fast but stable way until final failure of the joint.

Fatigue tests have been performed on single-lap composite bolted joints with two different thicknesses and four types of countersunk bolt heads, to assess the performance of the different configurations. All joints were tested at $R=0.1$ and at a frequency of 7 Hz and had a combination of bearing and fastener failure. Test results show the beneficial effect of higher plate thicknesses and the strong influence of the type of countersunk head on the joint fatigue performance. The application of the method allows the identification of the crack location and of the undamaged fatigue life length of each tested joint (from the test start to crack initiation).

The fatigue test results have been compared to static results performed on the same joint configurations. A clear correlation has been highlighted, with thickness and bolt head type influencing static and fatigue results in the same way. The relationship of the static results to the fatigue performances has been shown. In one joint configuration the reduction of 16% of the maximum load applied shifted the test outcome from static failure to infinite fatigue life. The importance of static bearing damage in fatigue has been highlighted. In particular, static bearing damage was present in all tested joints, since, in order to achieve fatigue failure, it has been necessary to apply maximum loads high enough to cause bearing damage in the plates.

A joint fatigue failure mechanism has been proposed as outcome of the investigation. This considers the role of the clamping force in the assembly, of the static bearing damage developed during the first cycle of the fatigue test, of the limited effect of the bearing fatigue damage and of the fatigue crack initiation and propagation in the bolts.

4.9. Publications

The work presented within this chapter regarding the monitoring method has resulted in the following publication:

“C. Stocchi, P. Robinson, S.T. Pinho, Using Strain Gauges to Monitor Bolt Clamping Force and Fracture in Composite Joints during Fatigue Tests, 15th European Conference on Composite Materials (ECCM15), Venice, Italy, 2012.”

It is envisaged that the contents of this chapter will be submitted for journal publication in the near future.

Chapter 5

Conclusions

In this thesis, the mechanical behaviour of two-bolt single-lap composite joints with countersunk bolts has been studied. The static behaviour has been investigated numerically (comparing the results with experimental tests), giving a deeper understanding of the complex interaction between the parts. The fatigue behaviour has been studied experimentally, developing a method to monitor the joint health status during the fatigue tests. A connection between static and fatigue joint behaviour and performance have been discovered. The effect of important parameters on the joint mechanical behaviour and strength have been studied, linking them to the damage micro-mechanisms and joint failure modes when possible.

The developed FE model should allow the industry to conduct more detailed analysis on bolted joints, in particular on the interaction bolt-hole. The use and the further development of a so detailed model may lead to a drastic reduction of the experimental testing required to validate a design solution. In this way, the focus of the experiments would shift from the characterisation of the design to the validation of the models.

It has been shown a clear link between joint parameters, stress distributions and failure mechanisms. This highlights the benefit that a deeper understanding of the

joint behaviour can bring to the design process. Knowing what triggers the diverse failure modes, the designer can increase the overall strength of the joint and, in case of overload, choose the most desirable failure mode.

A method to monitor bolt clamping force and detect crack initiation and propagation during fatigue tests has been developed. This method allows the study of loss of clamping force due to cyclic loading, extremely important for in service conditions, and identify crack initiation and propagation of the bolts, which correspond to a reduction of the mechanical performance of the joint. These are very important input for the design process which must guarantee the structural integrity of the joint for all the in-service life of the aircraft.

Chapter 6

Future work

6.1. Numerical work

The FE model presented in Chapter 2 predicts well the mechanical behaviour of bolted joints until the start of the bearing damage. A physically based bearing damage model would be needed to study the joint mechanical response until final failure. Different approaches have already been investigated, such as the use of complex composite damage models as the one developed at imperial for the second World-Wide Failure Exercise (WWFE-II) [92]. This has previously proven to be able of simulating in detail several types of composite damage and was ranked first in terms of blind predictions in WWFE-II [93]. Despite this, this damage model has been found in this case to be too complex for the implicit solver to converge since bearing damage is characterised by an accumulation of several types of damage in a limited space. In fact, the complexity of the failure process typical of bearing damage may deserve to be represented as a separate 'homogenised' failure mode in joint models, as modelling individually each crack is computationally prohibitive. Such an approach could take insertion from detailed and instrumented experimental bearing tests.

Once the bearing damage model is developed and validated, this could be used to extend the investigation about the effect of the parameters on the joint stress distribution. In addition to study the stresses around the holes, this would allow an investigation on how the parameters influence the joint in terms of the load at which the bearing starts, of how the bearing damage evolves and of the resulting stresses at which the bolts are subject to.

To simulate cracks in the bolts, the eXtendend Finite Element Method (X-FEM) could be used. This has already been tested on the full joint model but has shown severe convergence problems in case of bolts modelled with an elastic-plastic material. On a simpler and smaller version of the model, the X-FEM has shown to replicate with great accuracy the actual shape of a fully propagated crack obtained experimentally, even with an elastic-plastic material. Similarly, to simulate delamination between the plates' plies (even though delamination is limited in case of high clamping forces), it would be possible to define cohesive contacts between the plies.

Currently it is not possible to simulate in a convincing way, and with a physically based approach, fatigue tests on composite bolted joints. However, the connection found between the static and fatigue mechanical response of the joint suggests that it may be possible in some cases to extrapolate the fatigue performance from static simulations. It has been observed that, static bearing damage, developed in the first cycle of the test, may have an important role in fatigue. In addition, if high clamping force is applied, the mechanical behaviour of the joint seems to remain largely unchanged until crack initiation occurs, with fatigue bearing damage playing a role of minor importance. From these observations, as first approximation, It could be hypothesized that the fatigue damage develops only in the bolts, while the bearing damage occurs only statically when the maximum (or minimum) load is applied for the first time. Following this hypothesis, it could be possible to simulate the first cycle of the fatigue test (or more than a cycle to stabilise the joint behaviour) as a static test and use the values of stress found in the bolt (influenced by the simulated static

bearing damage) when the joint is subject to either the maximum or minimum load applied, as input to calculate the cycles to bolt crack initiation.

6.2. Experimental testing

The developed method has demonstrated to be able to monitor the clamping force and detect bolt crack initiation during joint fatigue tests. For this reason, it would be useful to extend the number of tested specimens to obtain a more comprehensive S-N graph for each investigated configuration, both in terms of cycles to crack initiation and of cycles to final failure. In this way, it would be possible to understand how the investigated parameters and the entity of the cyclic load influence both undamaged and total life of the joints.

It has been found that fatigue bearing damage did not have a major role in the mechanical response of the tested joints and that its entity was limited. To confirm this and to investigate more in detail the phenomena, a set of fatigue tests may be run. These should share the same joint configuration and cyclic load but be stopped at a different number of cycles. In particular, a test should be stopped after the first fatigue cycle and the others after increasing numbers of cycles. In this way, it would be possible to inspect (with fractography and x-rays) the composite damage at the edges of the holes and study the evolution of the bearing damage through the cycles, starting from the static bearing damage. In addition, dye penetrant inspection could be used to investigate the presence of initiated first thread cracks not visible to the naked eye.

In order to develop and validate a bearing damage model, a series of experimental bearing tests would need to be run. The tests would require several specimen configurations, different in the relevant parameters (such as stacking sequence, plate thickness, hole diameter, etc.) to understand their influence on the damage development. The tests would need to be stopped at different load levels and the holes inspected, reconstructing the evolution of the bearing damage.

Appendix A

Automatic Analysis Tools (AAT)

A.1 Tool Overview

To meet the objectives of this thesis and address additional problems, several FE analysis and parametric studies have been run. In particular, being the mechanical response of the joint highly non-linear, an analysis is necessary for each investigated configuration.

To make the investigations as efficient as possible, a series of tools has been developed for the automatic generation of FE models of composite bolted joints. The tools have been developed using the coding language Python, which allows the commands to be submitted directly to the Abaqus Kernel. All the different versions of the tools are composed by a main code, which contains all the command lines required to generate the models, and by an input file, which contains all the inputs, such as dimensions and parameters, for the specific joint configuration required by the user. Main code and input file, being separated, allow the user to use the main code with all the possible types of joint configurations while changing only the input file and having the possibility to keep different input files.

The versions of the tools are:

- AAT 3.0; for the automatic generation of single lap composite bolted joints with countersunk fasteners (as described in Chapter 2).
- AAT 3.0F; for an automatic and fast 2D axial-symmetric FE analysis of a bolted joint during the application of the clamping force.
- AAT 3.0P; for an automatic generation of single-lap joints with protruded joints, with metallic, composite or hybrid plates and with interference joining between bolts and plates.

A.2 Automatic Analysis Tool 3.0

This version of the AAT allows for an automatic generation of single-lap composite bolted joint models (Fig. A.1) as described in the Chapter 2. The main code has been developed to give the maximum flexibility in the choice of the joint composition.

The model developed is completely parameterised, which means that every dimension and parameter of the joint is included as a value in the input file. Some of these dimensions and parameters of the joint are:

- Plate thickness (t), width and length
- Distance between bolts and between bolt and run-out end (e)
- Bolt diameter (d)
- Bolt head height (h) and angle (θ)
- Vertical and horizontal offset of the bolts from the centre of the plates
- Length of the support plates
- Clearance between bolts and holes
- Coefficient of friction between plates and between plates and bolts
- Bolt clamping force

APPENDIX A. AUTOMATIC ANALYSIS TOOLS (AAT)

- Material properties
- Mesh details

In addition the tool offers some flexibility in the composition of the joint configuration:

- Possible to exchange position between the two bolts, selecting whether to have a bolt head or a nut next to the joint run-out (as used in Chapter 3).
- Number of plies and stacking sequence.

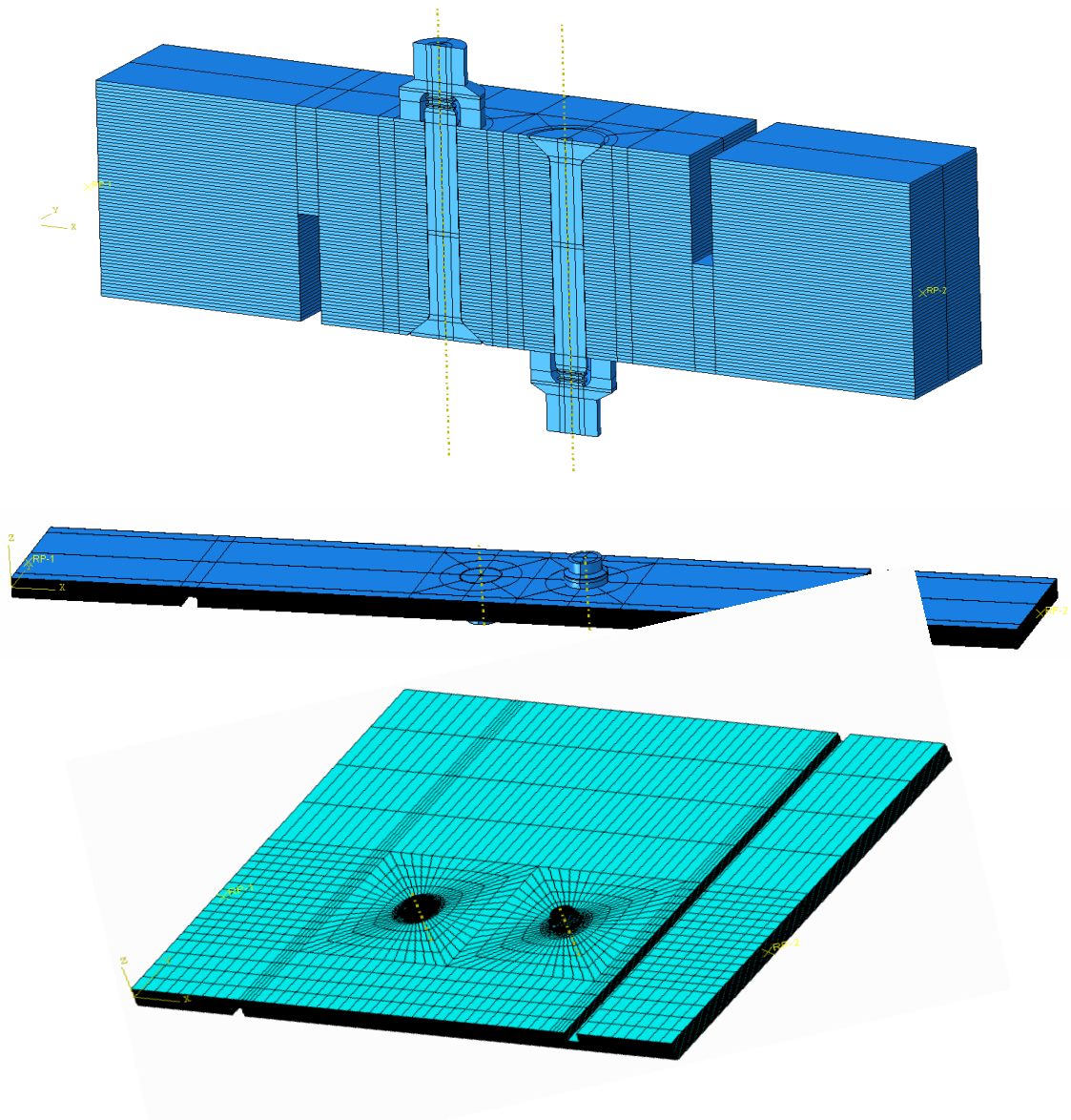


Figure A.1. Examples of joint configurations produced by the AAT2.0.

A.3 Automatic Analysis Tool 3.0F

The previous version of the AAT generates very detailed 3D models which requires several hours of run-time on a multi-processor computer to be analysed. The AAT3.0F tool has been developed to have a fast first assessment of the mechanical performance of plates and bolts during the joint assembly.

This tool uses a 2D axial symmetric model of a bolt and part of the plates to simulate the clamping-up of the bolts (Fig.A.2). The geometries of the bolt head and the plates are represented properly and the model features the same contact definition as the 3D model. The clamping force is applied from the bottom of the bolt.

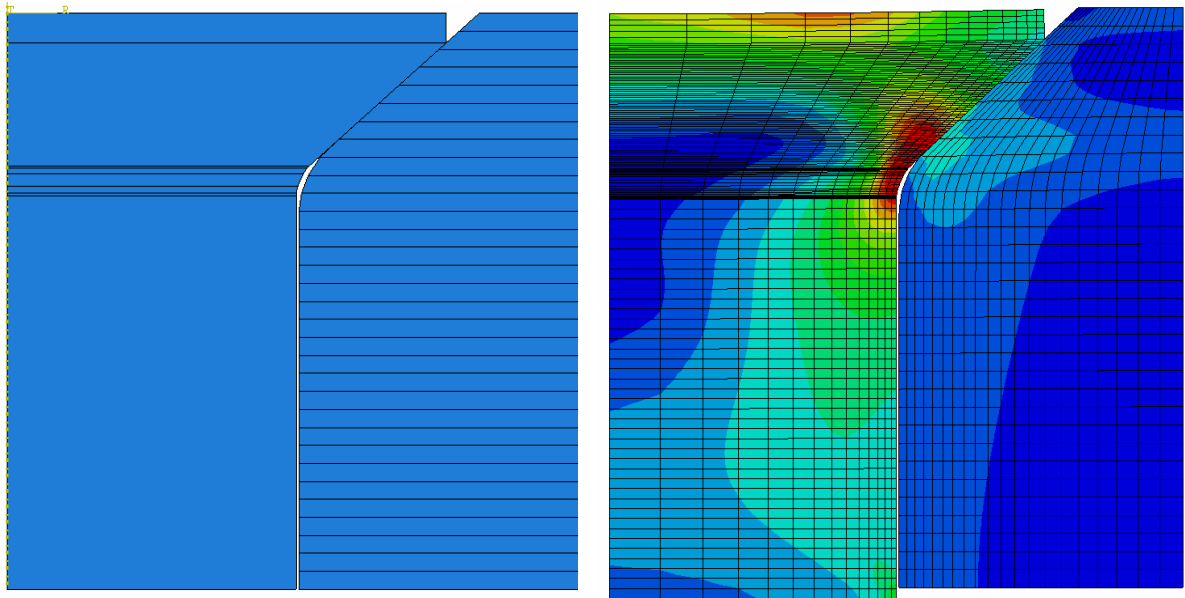


Figure A.2. Axial symmetric model produced by the AAT3.0F and correspondent von Mises stress from the analysis.

A.4 Automatic Analysis Tool 3.0P

This tool allows the automatic generation of fully parameterised models of single-lap joints with protruded bolts. The material of each plate can be chosen separately. In this way it is possible to have both plates made of composite materials, of metal or one for each type, having an hybrid joint. The joining between bolts and holes can be either with clearance or interference (Figure A.3). With this tool it is possible to study in detail the mechanical performances of the two plates and the behaviour of the joint (Figure A.4).

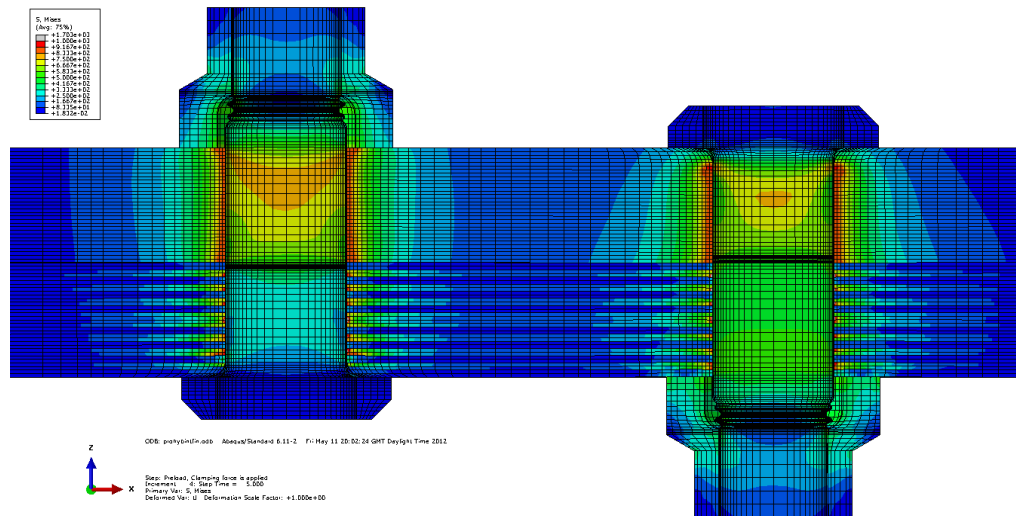


Figure A.3. Hybrid joint after the interference has been solved and the clamping force has been applied.

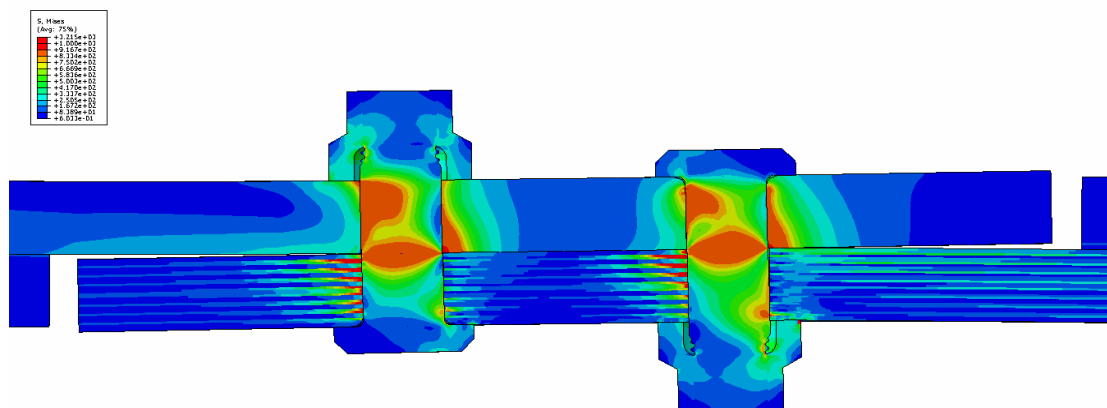


Figure A.4. Hybrid joint with the external load applied.

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