A DETAILED FINITE ELEMENT INVESTIGATION OF COMPOSITE BOLTED JOINTS WITH COUNTERSUNK FASTENERS

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Abstract

This paper presents a very detailed FEM model of a single lap shear composite bolted joint, with countersunk fasteners, under static tensile load. Parametric studies have been performed to study the influence of clamping force, coefficient of friction and clearance on the joint behaviour. It has been found that the model is able to identify correctly the joint critical locations and that the joint behaviour can be divided in five stages, which are deeply influenced by the three studied parameters.

1 Introduction

Bolted joints have been widely used in the aircraft industry for many years and, even with the recent and widespread introduction of composite materials, still have a key role in aircraft structures. In order to use composite bolted joints more efficiently and improve their design, a deeper understanding of the joint behaviour is needed. This can be achieved by running vast, well planned and time consuming experimental campaigns or by using a sufficiently detailed and flexible finite element model.

In the past several works have been published regarding the numerical and experimental study of composite bolted joints. Some of the most relevant and recent ones have been produced from the researchers involved in the BOJCAS project (Bolted Joints in Composite Aircraft Structures) [1,2,3,4], which has involved several universities around Europe.

Early attempts to numerically model composite bolted joints have been made approximating bolts to springs or rigid bodies, plates to shell elements [1] or even using combinations of 1D elements [5]. These methodologies can be numerically very efficient and fast, but do not consider the joints as a three-dimensional problem, giving approximate or incomplete results.

Several 3D models have been presented during the recent years. Following the increased computational power, Ireman, in 1998, developed a joint model [6] which illustrated that a three-dimensional approach is necessary to detect the stress-strain state around the holes. From there several researchers tried to add more details to the analysis. Tserpes et al. presented a joint model [7] with the ability to simulate damage in composites and McCarthy et al. included more geometrical detail [2], modelling the clearance between bolts and holes and studying the effect of this on the joint behaviour.

Despite the improvements, the effects of several key features, such as clamping force, coefficient of friction, clearance and joint geometric details on the joint behaviour still need further investigation.

This paper presents a very detailed FEM model of a single lap shear composite bolted joint (Fig. 1), with countersunk fasteners, under static tensile load. It discusses the results comparing them to experimental data and shows a parametric investigation of the influence of clamping force, coefficient of friction and clearance on the joint behaviour.

2 Numerical Model

The numerical model developed (Fig.2) has been produced with Abaqus 6.10 E.F. using a non-linear dynamic implicit formulation and a combination of reduced and full integration linear three-dimensional elements.

The model is composed of the following parts:

- 2 countersunk fasteners composed of anodised titanium (Ti-6Al-4V) bolts and steel nuts (shank diameter: 6.33 mm);
- 2 main plates made of unidirectional carbon fibre reinforced plastic (CFRP) with a quasi-symmetric stacking sequence (plate thickness: 5.888 mm) ;
- 2 CFRP support plates adhesively bonded to the main ones in order to avoid excessive bending.

The model represents the portion of specimen (Fig.3) between the two pairs of jaws in the physical test. The jaws and the gripped portions of the specimen are modelled as two rigid bodies connected to the opposite ends of the model, respectively. One of the rigid bodies has all degrees of freedom supressed (including rotations) while the other is free to move only along the main direction of the specimen. The bonding between main and support plates is represented using tie constraints.

The model is completely parameterised to easily study the effects of several parameters on the results, while its geometry and mesh (Fig.4) are sufficiently detailed to replicate the key features of bolts and plates. In the bolts the transition between heads and shanks is accurately modelled. The part of the thread not in contact with the nut is modelled as an axial revolution of the actual thread section. In the plates, 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. The clearance between the bolt shanks and the plate holes is also represented.

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. The CFRP is modelled with a linear elastic law as an orthotropic material with the orientation for each ply.

A full definition of the contact zones is implemented. This comprises of the contacts between the main plates, between bolts (heads and shanks) and plate holes and between plates and nuts. The contacts are solved using the penalty method. 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. These values have been obtained from specifically designed experimental tests.

The analysis is divided into two steps:

1. The clamping force is applied to the bolts using the ‘Bolt Load’ keyword. A layer of elements in the bolt is shrunk along the bolt axis until the sum of the reaction forces in the layer is equal to the desired clamping force.
2. The displacement-controlled tensile test is simulated by imposing a longitudinal displacement to the rigid body which has a free degree of freedom.

3 Results

Several FE analyses have been run using the model described in the previous section. The first aim of these simulations is to study the behaviour of the joint when the clamping force is applied and then when the displacement is imposed to the joint. The second aim is to investigate the change in 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 model has been validated using unsupported single lap shear experimental data from specimens with the same dimensions and features as the FEM model. The key parameters used in the simulation are:

- clamping force applied to each bolt = 15,000 N;
- coefficient of friction between composite plates = 0.2;
- clearance (difference between hole and bolt diameter) = 0.06 mm.

Figure 5 shows a good agreement between numerical and experimental data; this highlights the model’s capability to detect the key features of the joint behaviour, especially during the early-stage. These features are the No-slip, Slip and Full contact stages, which will be fully explained in the discussion section. While the first part of the behaviour is properly reproduced, the current model is not able to simulate the bearing damage, which occurs in the last stage of the test. A bearing damage model is under development and it will be included in a next version of the model. Since the model does not reproduce the bearing damage, the phenomenon driving the last stage of the simulation is the development of plastic strain in the bolt shanks.

After the clamping force is applied to the bolts in the model (Fig. 6) it is possible to see the bolt head partially sunk in the composite hole and the development of a von Mises stress concentration and plastic strain at the countersunk head root and at the first thread emerging from the nut.

As the displacement is imposed to the specimen, the model shows a primary bending along its length and a progressive separation of the plates (Fig. 7). Analysing the model section (Fig.8), a secondary bending of the bolt inside the plates can be noticed. The relative movement of the plates leads to the contact between the bolt and opposing sides of the hole in each plate. Two locations with high concentrations of von Mises stress and plastic strain can be identified in the bolts. These correspond to the countersunk head root and to the first thread from the nut. In the experimental tests 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 the associated plastic strain are found in the bolts while high von Mises stresses are predicted in the composite plates. Experimental results support this since residual bending of the bolts at that point and localised bearing damage at the edges of the holes can be observed.

The first parametric study has been run using the previous model but varying the coefficient of friction in order to study its effect on the joint behaviour. The coefficients of friction used are 0.01, 0.1, 0.2, 0.4 and 0.6. As can been seen from Fig. 9, having a higher coefficient of friction leads to a longer first stage of the behaviour, characterised by a higher stiffness, and to an increased load on the load-displacement curve.

The second parametric study investigates the effect of the clamping force on the joint behaviour. The clamping forces used are 1, 5000, 10000 and 15000 N. Fig. 10 shows a longer first stage of the behaviour, which is similar to what seen studying the coefficient of friction, but limited differences to high applied loads.

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 Fig. 11, increasing the clearance does not modify the first high-stiffness stage of the behaviour but it has the effect of delaying the start of the second stiff stage of the behaviour.

3 Discussion

From the numerical and experimental data presented in the previous section it seems possible to divide the joint behaviour in five stages (Fig. 12):

1. No-slip
2. Slip
3. Full contact
4. Bearing damage
5. Final failure

The No-slip stage has the highest stiffness and it is characterised by the absence of movement in the contact between the plates and by the load totally transferred by friction. The maximum load that can be carried only by friction has been found to be around 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 in this stage depends only 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 increment of the load applied. Because of the different diameters of bolts and holes and the distortions of the geometries of the joint parts by primary and secondary bending, the first contact between bolt and hole edges is on a limited surface. From that point the contact develops involving progressively a larger area until a full contact between bolts and hole edges is achieved. This has the effect of increasing the stiffness progressively and creating a smooth transition to the full contact stage. The length of the transition appears to be roughly proportional to the amount of clearance in the joint. The Slip stage seems to be long, in displacement, around the amount of clearance, which is the difference between the diameters of bolts and holes, plus the length of the transition zone. This is in agreement to what found from McCarthy et al. experimentally [3] and numerically [4]. It should be noted that, even if a nominal clearance of 0 mm is chosen, the joint may still have some little clearance due to the effect of the clamping force enlarging the plate holes. From the parametric studies performed in the previous section, it seems that stiffness and length of the Slip stage are not affected by the change of coefficient of friction or clamping force.

The full contact zone 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, this is due to the local compliance of the contact between bolt shanks and hole edges. The presented parametric study on the effect of the clearance seems to support this theory. The study shows that an increasing clearance leads to a lower stiffness in the full contact stage of the behaviour. This is probably because a higher clearance means more mismatching surfaces, in size and orientation, of bolt shanks and holes and, thus, a smaller area in contact.

The bearing stage is characterised by a reduced stiffness and by bearing damage occurring in the hole edges. Since no damage to the composite has been included so far, this stage is driven by the development of plastic strain caused by shear in the bolt shank where it is aligned to the faying surface.

The final failure of this joint generally results from a crack in the bolt head or in the first thread. This leads to a sudden drop in the load carried on by the joint. There may be other failure modes, such as pull-through of the bolts or excessive bearing damage, depending on the bolt geometry and the thickness of the plates.

4 Conclusions

This paper presents a detailed FE model of a single lap shear composite bolted joint, with countersunk fasteners, under static tensile load. The results from the model have been compared to experimental data and an investigation of the effect of the coefficient of friction, clamping force and clearance on the joint behaviour has been carried out.

The numerical results have a good agreement with the experimental data, especially in the first part of the test. The model identifies the countersunk head root and the first thread as the critical locations in bolts. In the experiments these are found to be the locations where cracks develop.

According to what was found in numerical and experimental data, the joint behaviour can be divided in 5 stages: (i) No-Slip, (ii) Slip, (iii) Full Contact, (iv) Bearing Damage and (v), Final failure. The stiffness of the No-Slip stage seems to depend only on the plate stiffness while clamping force and coefficient of friction define the maximum load carried out only by friction. The full contact stage is influenced by the clearance which seems to modify the stiffness of the joint.

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 will be included in a future version of the model.

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Fig.1. Specimen of a composite bolted joint for the experimental unsupported single lap shear test.

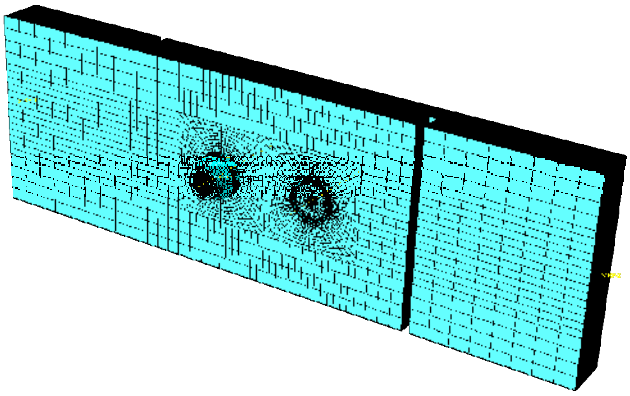

Fig.2. Finite element model of a composite bolted joint.

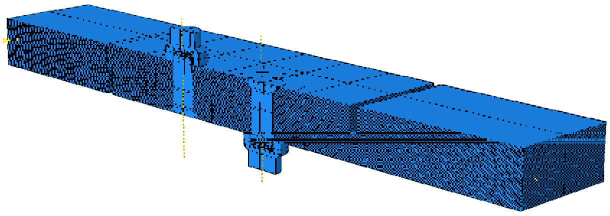

Fig.3. Section of the FE joint model.

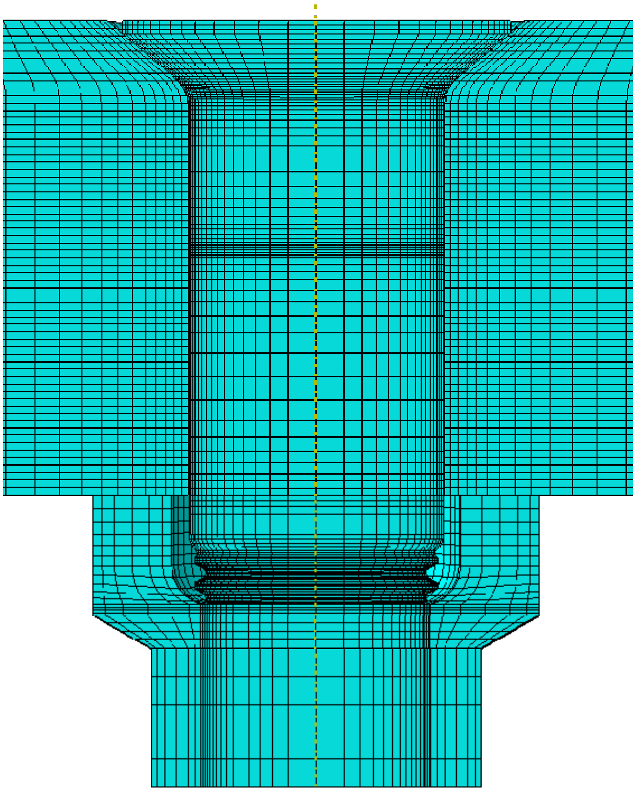

Fig.4. Mesh in the section of a bolt and plates in the FE model.

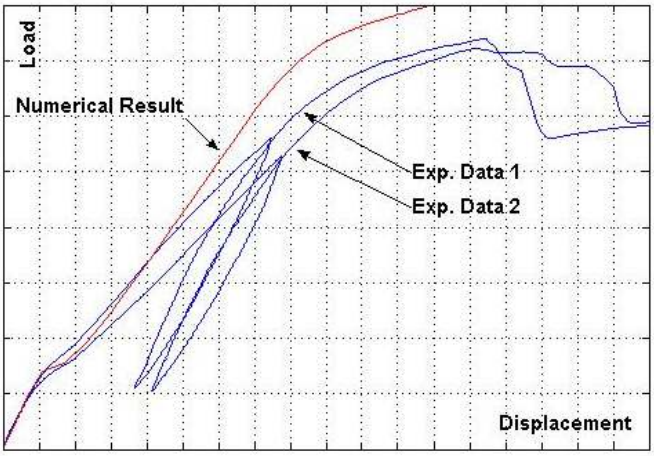

Fig.5. Comparison between unsupported single lap shear test data and Finite element results.

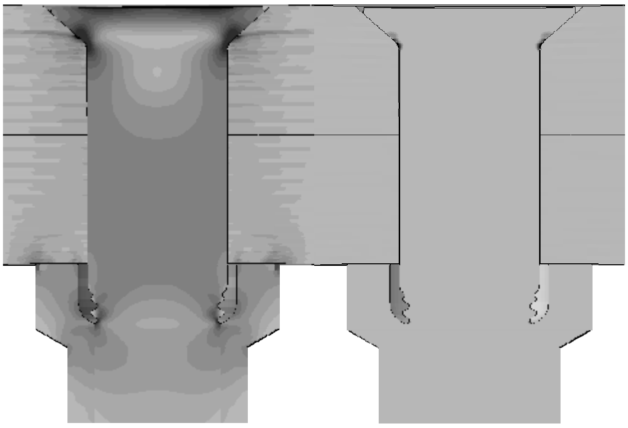

Fig.6. Von Mises stress and plastic strain in the bolt section after have applied the clamping force.

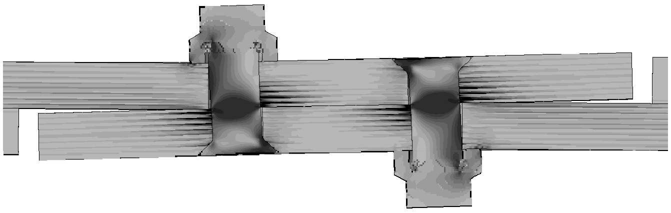

Fig.7. Primary bending in the model section when the external load is applied (von Mises stress as contour).

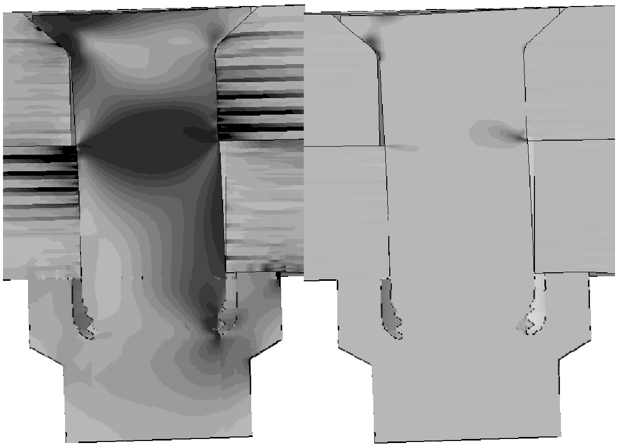

Fig.8. Von Mises stress and plastic strain in the bolt section when the external load is applied.

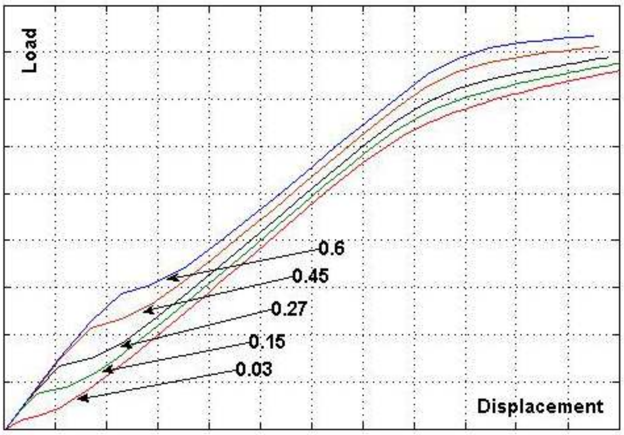

Fig.9. Parametric study of the effect of the coefficient of friction on the joint behavior.

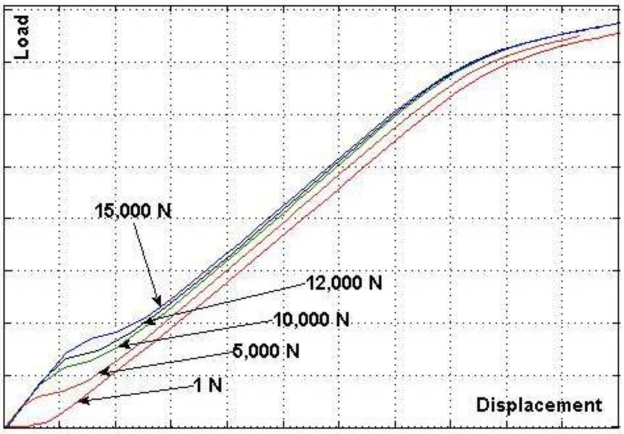

Fig.10. Parametric study of the effect of the clamping force on the joint behavior.

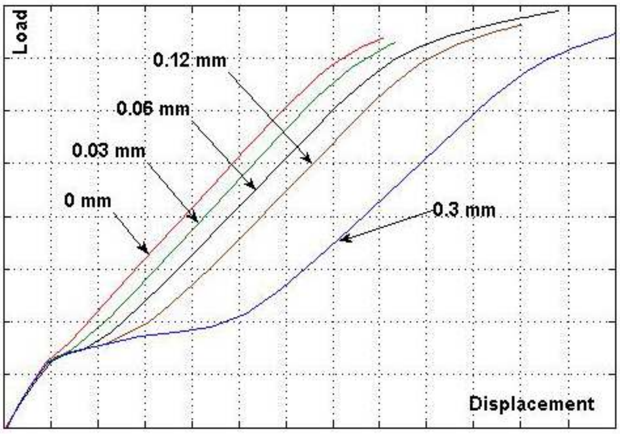

Fig.11. Parametric study of the effect of the clearance on the joint behavior.

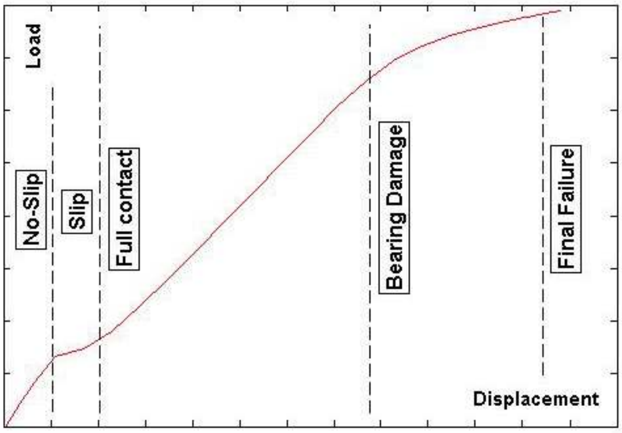

Fig.12. Joint behavior divided in 5 stages.

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