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

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ABSTRACT

This paper presents a very detailed FE model of a single lap composite bolted joint, with countersunk fasteners, under static tensile load. The stress states of the CFRP plates and titanium bolts are discussed, the evolution of the contact between the bolts and the holes is analysed, and the numerical results are compared to experimental data. Parametric studies have been performed to study the influence of bolt clamping force, coefficient of friction and bolt–hole clearance on the joint behaviour. It has been found that the model is able to identify correctly the critical locations in the joint (head–shank transition and first thread in bolts and edges of the holes at the faying surface for the plates) and reproduce with accuracy the experimental load–displacement test curves (including an unloading–reloading loop) up to the point where bearing damage occurs. A correlation between the joint stiffness and the contact status between bolts and holes has been found. Five stages have been identified in the joint behaviour: (i) *No-Slip*, (ii) *Slip*, (iii) *Full Contact*, (iv) *Damage* and (v) *Final Failure*. The results show that the joint stiffness is higher in the *No-Slip* stage than in the *Full Contact* stage, and that this is independent of coefficient of friction and bolt clamping force. The clearance controls the length of the *Slip* stage and modifies the joint stiffness in the *Full Contact* stage.

1. Introduction

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. Along with 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 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.

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. Ekh and Schön [1] 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 [2] or continuum shells [3]. 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 [4] 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. [5] improved Ireman's model including the clearance between bolts and holes in the study of joints with protruding fasteners. More recently Hühne et al. [6] 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. This research 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.

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Several attempts have been made to study numerically and experimentally the effects of geometrical features and parameters on the joint behaviour and strength. Ekh and Schön performed a numerical investigation of the effect of the distance between bolts on the secondary bending and strength of the joints [7] and an analysis of the load transfer in multi-row bolted joints [8]. McCarthy et al. performed extensive investigations into the effect of clearance on the joint mechanical response. They first 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 [9]. After this, they aimed to replicate the observed behaviour with a 3D FE model [10] 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 [11]. 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 investigated. Friction plays a major role in bolted joints, but the influence of the coefficient of friction between the plates on the joint behaviour is still largely unstudied. In addition, no exhaustive experimental or numerical investigation has been found in the literature on the effect of the bolt clamping force. Schön [12,13] 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 focused 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 preload, 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.

This paper presents a very detailed parametric FEM model of a single lap shear composite bolted joint (Fig. 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.

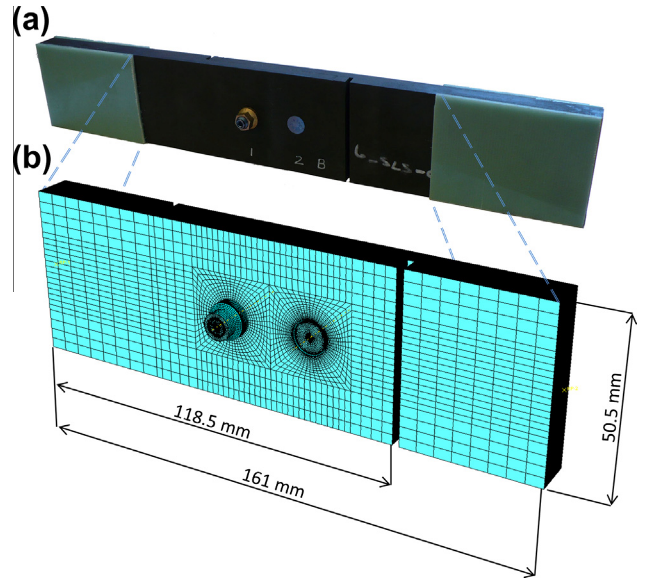

Fig. 1. (a) Specimen of a composite bolted joint for the experimental unsupported single lap shear test. (b) Finite element model of a composite bolted joint.

2. Numerical model

The developed 3D finite element model of a single lap composite bolted joint (Fig. 1) has been produced with Abaqus 6.10 [14] using a non-linear geometric dynamic implicit formulation. The specimen, as well as the model, is composed of the following parts (Fig. 2):

- 2 countersunk fasteners composed of anodised titanium (Ti–6Al–4V) bolts and steel nuts (shank diameter of 6.33 mm and countersunk angle of 100°).
- 2 main plates made of unidirectional carbon fibre reinforced plastic (CFRP) plies with a quasi-isotropic stacking sequence (plate thickness of 5.888 mm for 32 plies).
- 2 CFRP support plates adhesively bonded to the main ones in order to avoid excessive bending.

The model represents the portion of specimen (Fig. 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.

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 (Fig. 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