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A study of intra-laminar damage in double-lap, multi-bolt, composite joints with variable clearance using continuum damage mechanics

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ABSTRACT

A damage modelling approach, based on a continuum damage model (CDM) formulation, is proposed and applied to the problem of double-lap, multi-bolt, fibre-reinforced composite joints with variable clearances, subjected to quasi-static tensile loading. A new method of dealing with fibre failure is included in the CDM model, which is implemented in a commercial implicit finite element analysis code. The model is validated at element and structural levels by comparing with experimental data. It has been found that, for the joints examined in this paper, our formulation is capable of modelling development of damage from bearing failure onset all the way to ultimate catastrophic net-tension failure without numerical problems, which is an advance over previous work. The predictions from the CDM model of net-tension failure modes and ultimate loads are in good agreement with those from the experiments. Furthermore the model is capable of explaining some non-intuitive experimental findings, such as the larger energy absorption obtained in joints with higher clearances.

1. Introduction

Composite bolted joints (CBJs) are widely used in critical structures in aerospace and energy applications. Though competing with rapidly growing application of adhesive bonding and bonded repair techniques [1], CBJs are still of major interest, especially when thick composite parts are to be joined or where parts need to be disassembled for inspection or repair during the life time of the structure. The joints are the critical parts in the structure due to the stress concentrations and fibre discontinuities they introduce. Hence, various methodologies have been developed to investigate the structural response of the CBJs subjected to various loading conditions, by means of numerical analysis, e.g. finite element (FE) analysis, and/or experimental testing [2–4].

The two most well-known FE approaches for modelling fibre-reinforced polymer (FRP) composite material are Progressive Damage Analysis (PDA) [5] and continuum damage mechanics (CDM). PDA has been widely used for modelling CBJs, whereas the use of CDM is much less prevalent for CBJs in the open literature. In general, PDA is governed by material damage laws when an undamaged element material reaches a critical stress and/or strain state. Each element is assumed to be either in an 'intact' state or 'rupture' state. However, the CDM approach assumes that the element material transforms smoothly and gradually from the 'intact' state to the 'rupture' state. Ladeveze and Le Dantec [6] developed a CDM model based on a plane stress assumption for unidirectional fibre-reinforced composite plies to describe matrix micro-cracking and fibre/matrix debonding. O'Higgins et al. [7,8] and Frizzell et al. [9,10] then employed the model, enhanced it to account for fibre breakage, and extended it to a three-dimensional (3D) meso-scale to predict the damage response of notched CFRP composites under quasi-static and dynamic loading. This same CDM model was recently enhanced by combining a delamination model with the in-plane damage model in Nezhad et al. [11], and successfully applied to model low velocity impact of flat, unnotched CFRP panels manufactured from a high strain composite material used for fuselage barrels.

Recently, 3D FE modelling has been extensively used to study the damage response of CBJs [4,5,12–17], sometimes in combination with experimental work. Various types of joint have been investigated, such as single-lap, double-lap, single-bolt and multi-bolt joints, as well as joints with countersunk and protruding head bolts. Several of these studies have noted that bolt clearance plays a key role in the performance and damage tolerance of CBJs. McCarthy et al. [17] experimentally investigated the effect of bolt-hole clearance (from 0 μm to 240 μm) on the stiffness and strength

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of single-bolt, single-lap CBJs. The joint stiffness, 2% offset bearing strength, and ultimate bearing strength and strain were obtained in [17] according to ASTM [19]. The results indicated that clearances in the range used in aircraft applications can affect the 2% offset strength and ultimate bearing strain in protruding-head joints, but have little effect in countersunk joints. Based on this work, Egan et al. [20,21] carried out further assessment, using FE analysis, on the mechanical behaviour of single-bolt, single-lap countersunk joints. By providing a highly-detailed representation of stress state surrounding the countersunk hole, they were able to elucidate the failure mechanisms in countersunk joints.

Concerning multi-bolt composite joints, McCarthy et al. [15,22] carried out a series of experimental tests to investigate the effect of variable bolt-hole clearance on the quasi-static strength, fatigue life and failure modes in double-lap and single-lap CBJs containing three protruding head bolts. The effects on quasi-static ultimate strength were found to be relatively small, chiefly affecting the failure mode, and failure strain, while the failure load was only mildly affected. In contrast, the failure onset load, defined in [15,22] as the load corresponding to 30% loss in joint stiffness, had a strong correlation with clearance. The fatigue tests also showed that joints with one loose-fit hole had a significantly shorter fatigue life than joints with all neat-fit holes. McCarthy et al. [16] also developed a 3D FE PDA model of the multi-bolt, double-lap joints in [15,22], and surface strains and load–displacement response correlated well with the quasi-static experimental results. Bolt load plots showed that minor changes in clearance caused major changes in load distribution. The effects of clearance on damage progression were also studied. However, convergence problems meant that the numerical model could only follow the response up to just after initial bearing failure, which was only a small fraction of the damage and failure response observed in the experiments. The final failure mode in the experiments was net-tension failure, which the PDA model could not capture. Consequently, the ultimate load level was not captured either.

From the above, it can be seen that studies on bolted joints with CDM models are few in number compared to those using a PDA model. PDA models have exhibited convergence problems in previous investigations of joints, meaning that ultimate load cannot be predicted. In the present paper, a CDM model is suggested to alleviate these convergence difficulties. An important feature which has been found to improve the accuracy of predictions is the introduction of a new approach to derive the initial fibre failure strain. The model is capable of properly capturing the net-tension failure mode and ultimate load of multi-bolt, double-lap, protruding-head composite joints with different clearances, which the PDA model in [16] failed to do. The proposed CDM model is used to correlate the damage evolution with the joint stiffness variations during failure.

2. Overview of specimens

Brief details of the CBJ specimens studied are given here; for full details of the experimental set-up see [15,22]. Specimen dimensions are shown in Fig. 1. The ratios of the width (w), edge distance (e), and bolt pitch (p) to bolt diameter (d) were $w/d = 6$, $e/d = 3$, and $p/d = 4.5$ respectively. The laminates were manufactured from carbon–epoxy HTA/6376, and the quasi-isotropic lay-ups for the skin (centre) plate and splice (outer) plates were respectively $[45/0/-45/90]_{4s}$ and $[45/0/-45/90]_{2s}$, with nominal ply thickness of 0.13 mm. All tests were carried out with titanium alloy protruding-head bolts, secured with a steel nut and washer. The elastic material constants for the joint components are given in Table 1. In the tests, an axial displacement was applied quasi-statically to the splice plates while the skin plate was held stationary.

The four levels of clearance studied, labelled C1–C4, are shown in Table 2, which shows nominal clearance values, possible ranges on the reamer and bolt diameters according to the tolerances used on both, and consequent possible range on each clearance. The nominal clearances are 0 μm, 80 μm, 160 μm and 240 μm, representing, respectively, percentage clearances of 0%, 1%, 2% and 3% of the hole nominal diameter, 8 mm. The relatively large clearances C3 and C4 are slightly outside of recommended tolerance for aerospace applications, but may exist in practice if improper drilling or fastening procedures are followed. All the bolts had nominal diameter 8 mm, manufactured with f7 ISO tolerance. For the multi-bolt joints, six different clearance combinations are studied, as listed in Table 3. For example, the C1_C1_C1 case had (nominally) zero clearance in all holes, while the C4_C1_C1 case had a large

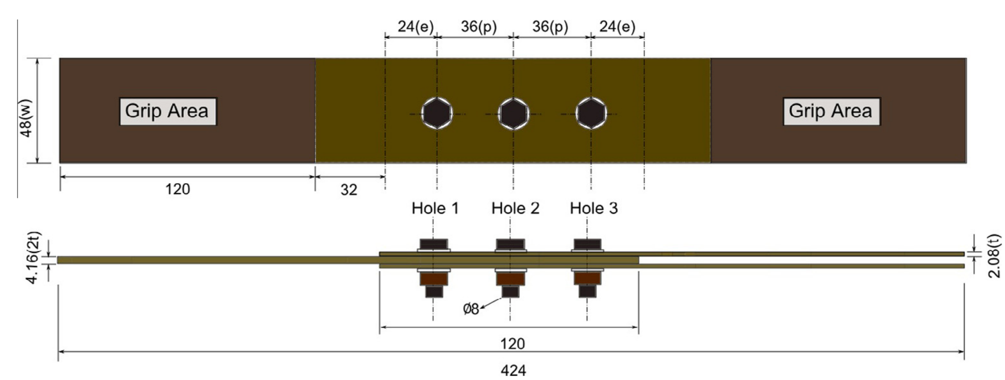

Fig. 1. Double-lap, multi-bolt, specimen geometry (all dimensions in mm).

Table 1
Material properties of HTA/6376 carbon–epoxy, titanium alloy and steel [15,22].

	E^0_{11} (GPa)	E^0_{22} (GPa)	E^0_{33} (GPa)	G^0_{12} (GPa)	G^0_{13} (GPa)	G^0_{23} (GPa)	ν_{12}	ν_{13}	ν_{23}
Lamina	140	10	10	5.2	5.2	3.9	0.3	0.3	0.5
	E (GPa)	υ							
Titanium alloy	110	0.29							
Steel	210	0.3							