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Load sharing in single-lap bonded/bolted composite joints. Part II: Global sensitivity analysis

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ABSTRACT

Bonded/bolted joints in composites are potentially stronger and more durable than the underlying bonded and bolted joints separately. While recent experimental work has revealed that the most significant "across-the-board" improvements (compared to *both* constituent joints) are obtained when there is substantial load sharing between the adhesive and bolts, there is currently limited understanding of how load sharing works and how it can most effectively be achieved. In order to answer this question, this work presents an extensive global sensitivity analysis of a computational model of a single-bolt, single-lap composite joint containing an elastic–plastic adhesive. This model was previously developed and validated in part I of the paper. The objective of the sensitivity analysis was to quantify the relative importance of the different joint design parameters (factors) in load sharing. It was determined that adhesive yield strength is singularly the most important factor, by between 2 and 9 times depending on the level of load applied to the joint. The joint E/D ratio, adhesive hardening slope and adhesive thickness were found to be other significant factors influencing load sharing. For designs in which the adhesive overlap did not fully plasticise, no significant proportion ($\leqslant 10\%$) of the applied load was found to be transferred to the bolt.

1. Introduction

In order to make useful composite structures, it is often required to join two or more components together. This is traditionally done using either adhesive or bolts, in what are called bonded joints and bolted joints, respectively. Although each method has unique advantages and disadvantages, bolted joints are currently the preferred choice in primary aircraft structures [1]. This is due in large part to the difficulty of certifying bonded joints, which are susceptible to a type of adhesive defect known as kissing bonds [2]. Contemporary non-destructive evaluation (NDE) methods are not sufficiently capable of detecting this type of defect [3,4]. Furthermore, bonded joint performance is relatively sensitive to temperature and moisture fluctuations [5]. Unfortunately, the use of bolted joints comes at a price, since the bolts impose a significant weight penalty on the structure. In addition, the brittle nature of many composite materials means that a significant number of bolts and/or thick laminates are needed to limit the developed stress concentrations at the bolt holes.

A possible alternative that has recently garnered interest consists of combining bonding and bolting in what is known as a bonded/bolted joint or a hybrid joint. This configuration could help to mitigate some of the certification concerns surrounding bonding. Furthermore, a number of studies have shown that bonded/bolted joints can potentially achieve greater static strength [6–10] and fatigue strength [6,8,9] than the underlying bonded and bolted joints separately. If a bolted joint is taken as baseline, a reduction in the number of bolts could thus be feasible. An important conclusion in the literature is that the greatest "across-the-board" strength improvements (compared to *both* constituent joints) are obtained when there is substantial load sharing between the bolt and adhesive load paths [7,8,11].

It must be stressed at this juncture that a bolted joint can potentially be improved by the addition of a strong, stiff adhesive, even in the absence of load sharing. This relies on the bonded joint being stronger than the bolted joint. However, in such cases the bonded joint strength will not necessarily be improved, and the joint strength simply becomes equivalent to the bonded joint strength. When load sharing exists, the strength of *both* the bonded and bolted joints can potentially be improved. Bonding/bolting is therefore of particular interest in cases were the bolted joint strength exceeds the maximum strength of the equivalent bonded joint.

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Despite the potential benefits of load sharing *in specific design cases*, there remains the obstacle of achieving it. As shall be shown in this paper, relatively few joint designs are capable of achieving substantial load sharing. This is corroborated by a number of experimental studies which report bonded/bolted joint initial failures that correspond to the underlying bonded joint strength, after which the joint behaves like a bolted joint [7,8,10]. Such behavior indicates an independent functioning of both load transfer mechanisms and the absence of load sharing. It is thus of interest to understand exactly when and how load sharing can effectively be achieved in bonded/bolted joints.

A few researchers have previously touched on the load sharing question. Kelly [6,7] used detailed 3D finite element models (FEM) to show the influence of different design parameters on load sharing. By varying one parameter at a time, he was able to show the effects on load sharing of the adhesive material, adhesive thickness (positive effect), E/D ratio (negative effect) and laminate thickness (positive effect). These effects were found to be monotonic. However, bolt-hole clearance and clamp-up were not considered and this *qualitative* analysis did not provide any indication of the relative importance of the design parameters nor account for interactions between them. Paroissien [12,13] similarly varied one input at a time in his analytical model. The effect of each was described as either "weak" or "strong". The same effects found by Kelly were reported, however, the simplicity of the particular model used meant that many possibly important design parameters and joint behaviors were ignored. Both of these studies can be classified in the *local* sensitivity analysis (gradient-based) bracket.

In this work, a *global* sensitivity analysis was conducted using a variance-based statistical method. A *quantitative* assessment was thus made of the importance of the various bonded/bolted joint design parameters in load sharing, including the effects of interactions. The subject of the analysis was the computational model presented in part I of the paper [14].

2. Problem description

The joint configuration studied was a single-lap bonded/bolted composite joint. This configuration, adapted from the ASTM D5961 standard [15], consists of two composite laminates (substrates) that partially overlap and are joined in the overlap region by means of adhesive and one or more bolts. Only the single-bolt case was considered as this is a common test configuration in civil and military engineering standards [15,16]. The load case of interest was uniaxial tensile loading. Although in reality a doubler would be bonded to the grip region of each substrate to permit installation in a tensile testing machine, it was shown in part I [14] that ignoring this region altogether in the model and assuming a clamped boundary condition at the grip edge is an adequate representation. A schematic of this configuration is shown in Fig. 1. The parameters that define the joint geometry are thus the substrate length L, substrate width W, substrate thickness t, adhesive thickness t_a, substrate free length L_f, overlap length L_a, edge distance E, hole diameter D and bolthead diameter D_h.

The composite and bolt materials were kept constant throughout the study. The former is Cycom 5320 carbon fiber unidirectional prepreg, whose properties are given in Table 1, while the bolt is made of steel ($E = 205$ GPa, $\nu = 0.3$). Note that only a single quasi-isotropic layup of $[45/\text{-}45/0/90]_{4s}$ was considered for both substrates in order to make the sensitivity analysis tractable. To account for the effect of different laminate stiffnesses, the ply thickness was allowed to vary to simulate a range of laminate thicknesses.

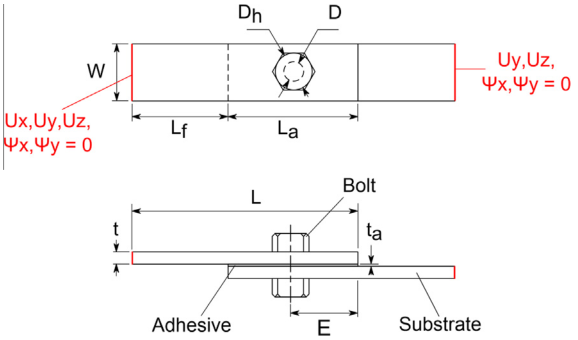

Fig. 1. Single-bolt, single-lap joint geometry.

Table 1
Cytec 5320 CFRP tape properties [14].

E_{11} (GPa)	$E_{22} = E_{33}$ (GPa)	$G_{12} = G_{13}$ (GPa)	G_{23} (GPa)	ν_{12}	ν_{13}	ν_{23}
141	9.70	5.10	3.40	0.33	0.33	0.44

3. Model description

A detailed computational model of a single-bolt, single-lap bonded/bolted composite joint, called the *Global Hybrid Joint Method* (GHJM), was developed in part I of the paper [14]. This model follows an equivalent single layer (ESL) approach with the laminates modeled as shells. The bolt is modeled as a beam while the adhesive is modeled as an isotropic continuum solid. The model is solved using the displacement based finite element method in ABAQUS, subject to the boundary conditions specified in Fig. 1. It was shown in part I that the model predictions compare satisfactorily with both a detailed 3D finite element model and an experiment, while providing computational savings of >95% compared to the former.

4. Global sensitivity analysis

A global sensitivity analysis (GSA) was performed of the GHJM in order to quantitatively assess the importance of the various model input factors in load sharing. Load sharing in the context of the current work is defined as the proportion of the *total load transferred by the bolt* to the overall load transferred by the joint. The term *total* is emphasized since load can be transferred by the bolt in two ways:

(a) Through friction between the bolthead and the substrate outer surfaces.
(b) Through a combination of friction and normal contact forces between the bolt shank and hole bearing surface.

The first type of bolt load transfer requires a clamp-up force in the bolt. Even when this load is extremely high (e.g. 8 kN), only a relatively small, pre-determined amount of load can be transferred in this way (assuming a coefficient of friction of 0.2, the bolthead load would be at most 1.6 kN in this case). The second type of bolt load transfer requires contact between the bolt shank and the hole bearing surface. This type is theoretically able to transfer a large amount of load, which increases as the joint deforms. The total bolt load is the sum of these two components and is equal to the bolt shear load in the adhesive center plane.

A variance-based GSA method was chosen for the sensitivity analysis as this permits consideration of general nonlinear, non-monotonic models without making underlying assumptions about