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Load sharing in single-lap bonded/bolted composite joints. Part I: Model development and validation

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ABSTRACT

The combination of a bonded joint and bolted joint can potentially result in a joint that is stronger and more durable than either constituent separately. Experimental studies have demonstrated that the greatest "across-the-board" improvements (compared to *both* constituent joints) are obtained when there is substantial load sharing between the adhesive and bolt. However, in practice few bonded/bolted joint designs experience load sharing, with the adhesive transferring most of the load. This work consequently deals with the problem of achieving substantial load sharing in bonded/bolted joints. The joint type studied was a single-bolt, single-lap composite joint containing an elastic–plastic adhesive. The research aim was to identify the most significant design parameters contributing to load sharing and to quantify/rank their importance. To accomplish this, a global sensitivity analysis was conducted of a suitable computational model. In part I of this two-part paper, this model is described and is validated both experimentally and against a high fidelity three-dimensional finite element model. The model predictions are shown to correspond well with both the experiment and high fidelity model, while reducing the computational cost by >95% compared to the latter. The validated model is subsequently used in the sensitivity analysis presented in part II.

1. Introduction

Advanced composite materials have been widely adopted in the aerospace industry owing to their excellent specific stiffness and strength. Nevertheless, the brittle nature of many composite materials means that mechanical joining of composite structures remains problematic. Large numbers of bolts and/or thick laminates are required to limit the stresses around bolt holes, significantly impacting structural weight. Adhesive bonding, while a desirable substitute, is currently difficult to certify as a standalone joining mechanism on primary aircraft structures. This is due to associated problems such as kissing bonds [1], hygrothermal sensitivity [2] and a lack of suitable non-destructive evaluation (NDE) techniques [3,4].

An interesting alternative consists of combining bonding and bolting in what is known as a bonded/bolted joint or a hybrid joint. A number of experimental studies have shown that such joints can potentially achieve greater static strength than the underlying bonded and bolted joints separately [5–9]. Fatigue life may also be improved [5,7,8]. Compared to a bolted joint, this could conceivably reduce the required number of bolts and thus improve structural efficiency. A recurring conclusion in the literature is that the most significant "across-the-board" strength improvements (compared to *both* constituent joints) are obtained when there is substantial load sharing between the adhesive and bolts [7,10,11].

Unfortunately, few bonded/bolted joint designs experience load sharing. This is evident from a number of experimental studies [6,7,9] in which the bonded/bolted joint initial failure corresponds to the bonded joint strength, after which the joint behaves like a bolted joint. Such distinct behavior is indicative of little to no load sharing. In addition, in part II of this study [12] it is shown that only a small region of the studied design space achieved substantial load sharing. It is therefore of interest to be able to predict and design for load sharing in bonded/bolted joints.

A number of analytical and numerical models currently exist for predicting load sharing. Only the models that consider single-bolt, single-lap joints shall be discussed, as this is the configuration of interest in the current work. This restriction is justified by the fact that single-lap, single-bolt joints are a standard test configuration in both civilian and military bolted composite joint standards [13–15]. Such joints present an interesting test case since they exhibit a range of complex effects such as secondary bending and bolt rotation, while being simple enough to allow the results to be readily understood, compared and interpreted.

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The analytical models in the literature [10,11] are extensions of the classical two-dimensional bonded joint model of Goland and Reissner [16] and are solved using the matrix displacement method. This allows the bolt to be represented in the analysis by a set of springs. Although efficient, these models ignore numerous design parameters such as bolt-hole clearance, bolt clamp-up and pressure-sensitive yield of the adhesive that could potentially be important in load sharing. Furthermore, the spring stiffness assigned to the bolt must be determined either experimentally or using a more detailed three-dimensional model.

The numerical models, meanwhile, consider the bonded/bolted joint in three-dimensional space. They are either (a) based on beam/plate theory and solved using the Rayleigh–Ritz method [17] or (b) based on three-dimensional elasticity and solved using the finite element (FE) method [6,7,18]. The first approach suffers from low computational efficiency when applied to bonded/bolted joints due to the large displacements and stress gradients incurred, leading to slow convergence of the solution and a large, dense stiffness matrix that requires considerable numerical operations to evaluate [19]. Furthermore, the consideration of contact requires considerable simplification. Unquestionably, three-dimensional solid FE models provide the most general, realistic and accurate analysis. Such models, which will be referred to as 3D FEM in the rest of the paper, have demonstrated good agreement with experimental measurements of load sharing [6]. Nevertheless, they are prohibitively costly for direct use in more extensive sensitivity analyses or optimization.

Using the above models, a number of researchers have previously touched on the load sharing problem. Kelly [6,7] used detailed 3D FEM to show the influence of various parameters on load sharing. However, he did not consider the effects of bolt-hole clearance or clamp-up and his qualitative analysis did not provide any indication of the relative importance of or interaction between design parameters. Paroissien [20] likewise varied one parameter at a time using an analytical model. He described the effect of each as either "weak" or "strong". Due to the simplicity of his model, however, many possibly pertinent design parameters and joint behaviors were ignored. Both these studies can be classified in the *local* sensitivity analysis (gradient-based) bracket.

Ideally, a *global* sensitivity analysis should be performed so that the entire volume of the design space can be explored. Such an analysis should provide a quantitative assessment of the importance of the various design parameters (factors) and take into account any interactions between design parameters. Two key missing elements are thus identified in the literature:

1. An efficient model of a bonded/bolted joint that takes into account all of the major factors potentially affecting load sharing, including clearance, bolt clamp-up and nonlinear adhesive behavior.
2. A robust sensitivity analysis of load sharing that considers all of these major factors, provides a quantitative assessment of their importance and accounts for possible interactions between them.

In this first of a two-part paper, the development and validation of an efficient computational model is addressed.

2. Problem description

The physical problem considered is a uniaxial tensile test of a single-lap bonded/bolted composite joint. The studied configuration is adapted from the ASTM D5961 standard [15] and consists of two composite laminates (also called substrates) that partially overlap and are joined in the overlap region by means of adhesive and one or more bolts. A doubler, having the same material and layup as the substrates, is bonded to the grip end of each substrate to minimize the eccentricity that would otherwise result when installed in a testing machine. Only the single-bolt case is considered, for the reasons outlined in Section 1. A schematic of this configuration is shown in Fig. 1. The parameters that define the joint geometry are the substrate length L, substrate width W, substrate thickness t, adhesive thickness t_a, substrate gripped length L_g, substrate free length L_f, overlap length L_a, edge distance E, hole diameter D and bolthead diameter D_h.

3. Finite element model

In order to simultaneously account, in a detailed manner, for the complex geometry, nonlinear behavior and contact that exist in a single-lap bonded/bolted joint, a numerical solution technique is required. The best suited technique for taking into account all of these phenomena is the displacement based finite element method. It was thus decided to develop a suitable model in the commercial finite element software ABAQUS, in order to leverage both the efficient contact algorithms of the software and the ability to implement user defined subroutines.

To achieve the desired computational efficiency, an equivalent single layer (ESL) approach was used in a similar vein to Gray et al.'s *Global Bolted Joint Method* [21]. In this FE model, the authors used shells/beams to efficiently model the laminates/bolts respectively. In the current work, Gray et al.'s model is extended to take into account bolthead clamp-up and bonding. As will be described, the new method, which shall be called the *Global Hybrid Joint Method* (GHJM), uses a single layer of quadratic solid elements to simulate the adhesive.

3.1. Element choice and mesh

The GHJM consists of four main components: the top laminate, the bottom laminate, the bolt and the adhesive. These are modeled as Reissner–Mindlin shells, Timoshenko beams and continuum solids respectively. The corresponding elements are designated S8R, B32 and C3D20R in ABAQUS. Quadratic element shape functions are used to provide a fast solution convergence rate. To simplify the analysis, the grip regions are not considered; Saint Venant's principle is invoked to justify their omission. A typical GHJM mesh is shown in Fig. 2.

To limit the required number of elements, biased meshing is used for the laminates and adhesive, with an increased mesh density in regions that experience significant stress and displacement gradients. This includes the vicinity of the hole and the overlap edges. An extensive convergence study was performed and showed that a single layer of *quadratic* solid elements through the adhesive

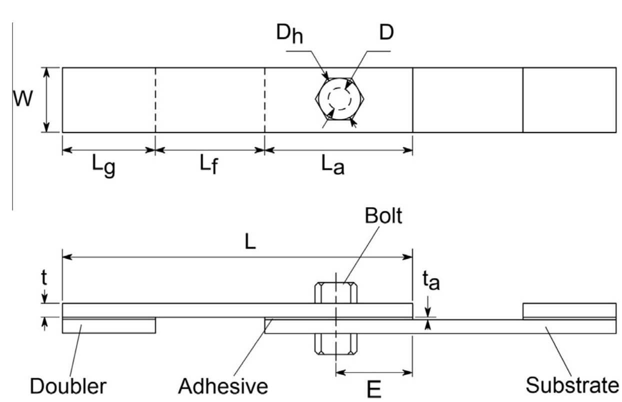

Fig. 1. Single-bolt, single-lap joint geometry.

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