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Tensile strength of open-hole, pin-loaded and multi-bolted single-lap joints in woven composite plates

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ABSTRACT

The prediction of the tensile strength of multi-bolted joints uses characteristics that are obtained from the open-hole tension (OHT), bolt-filled hole tension (FHT), pin-loaded tension (PLT) and single-bolt single-lap joint (BJ) tests. However, the relative relevance of each of these tests to multi-bolted joints is not clear. This investigation aims to fill the gap by performing these tests on carbon/epoxy and glass/epoxy laminates with quasi-isotropic and cross-ply configurations and on an Al-6065 aluminum alloy. It is found that the highest strength achieved by a multi-bolted joint corresponds to the OHT strength. The number of bolts required to achieve this upper bound depends on the material characteristics. The Al-6065 alloy achieves the OHT strength with two bolts, whereas the composites require up to four bolts. Narrower specimens require fewer bolts to achieve the OHT strength. The stiffness and strength of the BJ and PLT are comparable for Al-6065. However, for the composites, BJ has a lower stiffness but a higher strength than PLT. The pin contact force triggers delamination initiation and propagation in the PLT, whereas the tightened bolt in the BJ suppresses the delamination. In addition, the rotation of the bolt explains the lower stiffness of the BJ.

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1. Introduction

Mechanical joints are the weakest link of composite structures. Standard static tests show that in terms of strength retention, a mechanical joint made of an aluminum alloy will largely outperform a quasi-isotropic carbon/epoxy composite that was intended to replace it in structural applications. These assessments have not prevented the ongoing success of fiber reinforced plastics (FRP) over metal alloys counterparts in aeronautic applications. Essentially, the top reasons for such success are the proven superiority of the long-term mechanical performance, if equal weight is considered, and the fact that fewer parts must be assembled, which reduces the final cost. The second reason is supported by the maturity and advances made in composite manufacturing, such as automatic fiber placement to produce massive complex composite structures in a single part [1]. Indeed, FRP's present manufacturing technology allows for the integration of many parts into a single continuous part, thereby reducing the number of connections, which usually constitute the weakest link in primary structures. According to Harris et al. [2], the redesign of the tail with carbon/epoxy composites for the military transport aircraft C-17 (Boeing and McDonnell Douglas) yielded a 90% part reduction, 80% fastener reduction and weight and cost savings. Soutis [3] reported similar benefits for the military cargo Airbus A400M. However, the need for mechanical fastening remains inescapable and hence is a significant source of concern, as expressed by Hart-Smith [4], who stated that "*[t]he most appropriate way to design aerospace structures was to design the joints first and to fill in the gaps in between (the basic structure) afterwards*". Nelson et al. [5] noted that the efficiency of a composite bolted joint is lower than that of ductile metals and interpreted this behavior in terms of fracture mechanics concepts, particularly crack and damage initiation and propagation in isotropic versus anisotropic laminated composites. Duthinh [6] reviewed the important differences between the behavior and design of steel and FRP connections and found that the stress concentration at a circular hole is significantly larger in FRPs than in isotropic materials. According to Duthinh [6], plasticity in ductile metals relieves the stress concentration and causes it to have a small effect on the net failure stresses, but such ductile behavior does not exist for FRPs. Hart-Smith [4] proposed a good illustration of the relative efficiency of a bolted joint in ductile, fibrous composites and brittle materials, as shown in Fig. 1, which is an adaptation of Hart-Smith's diagram. The joint efficiency is defined as the ratio between the joint strength (reported to the nominal cross-section) and the standard unnotched strength of the material. Although the commonly preferred failure mode for bolted joints is bearing failure, the strongest possible failure mode per unit laminate width (W) is always the net-section tension [4].

It appears from the open literature that the ease of experimental testing and analysis has led to numerous investigations of single-bolt bolted joints. However, in real applications, aircraft bolt fastening consists of multiple bolts and multiple rows. Consequently, many studies have been extended to multi-bolted joints [7–15]. Crews and Naik [7] found that within multi-fastener joints, fastener holes might be

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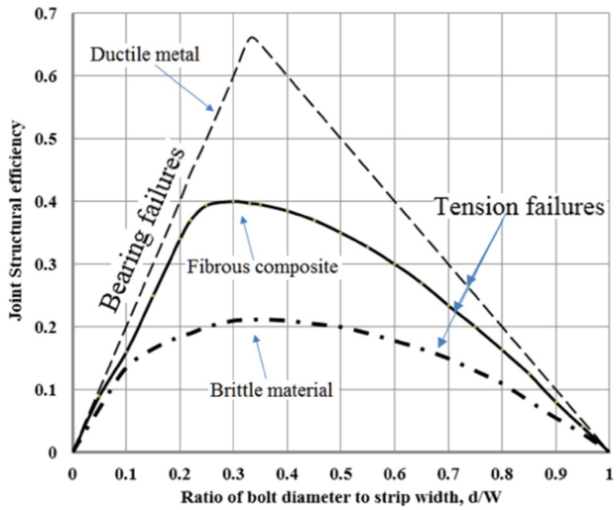

Fig. 1. Relative efficiencies of bolted joints in ductile, fibrous composite and brittle materials according to Hart-Smith [4].

subjected to both bearing loads and loads that bypass the hole. The ratio of the bearing load to the bypass load depends on the joint stiffness and configuration. McCarthy [9] developed a 3D finite element model of a multi-bolt composite joint and incorporated a full non-linear contact analysis at each bolt–hole interface and a progressive damage model for the composite material. That method [9] was capable of correctly accounting for both the bearing and bypass stresses in the presence of damaged material properties and the load re-distribution that occurs after bearing failure at one or more holes. Liu et al. [11] assumed that in most situations, the joint area was divided into several regions containing the original number of rows but only one column of fasteners and proposed an analytical model to predict the load distribution in a multi-bolt single-lap thick laminate joint. The analysis considered the changes in the fasteners' flexibility and the plates' flexibility that were introduced in the thick laminate single-lap joint. Starikov and Schon [8] conducted an experimental study on composite bolted joints under tensile and compressive loading using up to six titanium bolts (two columns of three bolts each). The results showed that the specimens that were joined by six bolts in either a single or double lap configuration displayed the highest quasi-static tensile and compressive strengths. However, the multi-row joints broke in the catastrophic net-section failure mode, whereas the single-row specimens failed in the bearing mode. Feo et al. [12] presented the results of a numerical analysis of different types of bolted composite joints with different geometries that were subjected to tensile loads. They examined the distribution of shear stresses among the different bolts by varying the number of rows of bolts and the number of bolts per row. It was concluded that in multi-bolt joints, the load distribution was affected by varying the bolt position, bolt-hole clearance, bolt-torque or tightening of the bolt, and the friction between member plates and at the washer–plate interface.

Open-hole tension (OHT), bolt-filled hole tension (FHT), pin-loaded tension (PLT) and single-bolt single-lap bolted joint (BJ) are basic tests that are used to provide the mechanical characteristics required for analytical modeling and finite element simulation [16–25]. For instance, the ASTM standards for OHT and FHT tests and practice [26,27] are commonly used in the aerospace industry to generate data used for fastened parts. This investigation addresses the tensile behavior of OHT, FHT, PLT, single-bolt BJ and multi-bolt BJ. The experimental results are expected to highlight more details that will help future analytical modeling and finite element simulations. They are also the first part of an extensive investigation into the performance of bolted, bonded and hybrid bolted/bonded structures under static and fatigue loading.

2. Experimental procedures

Carbon-fibers reinforced epoxy (CFRE) and glass-fibers reinforced epoxy (GFRE) composites are manufactured by the vacuum assisted resin infusion (VARI) process using a commercial Araldite epoxy resin system. The CFRE composite laminates are composed of 12 plies of 3 K plain wave carbon fabric with a 193 g/m^2 (5.7 oz/yd^2) surface weight. The GFRE composite laminates are composed of 12 plies of E-glass woven satin 7781 style with a 295 g/m^2 (8.71 oz/yd^2) surface weight. For CFRE and GFRE laminates, the woven plies are oriented to obtain the quasi-isotropic and cross-ply laminate configurations as shown below:

Quasi-isotropic symmetric sequence:	$[(0/90)/(\pm45)/(0/90)/(\pm45)/(0/90)/(\pm45)]_S$
Cross-ply symmetric sequence:	$[(0/90)/(0/90)/(0/90)/(0/90)/(0/90)/(0/90)]_S$

In the stacking sequence shown above, (0/90) or (±45) indicates a single woven ply. For all laminates, the warp side is oriented toward the zero direction. To construct the quasi-isotropic laminates, a (0/90) woven ply is simply rotated to obtain a (±45) ply. Table 1 shows the average fiber volume fraction (V_f), void volume fraction (V_v) and thickness along with the corresponding standard deviation (STD). The obtained values in Table 1 are representative of laminates usually manufactured by the VARI process. V_v is determined following the procedures recommended for the qualification of composite materials [28] and specifically outlined in ASTM D2734 [29], which require the use of Eq. (1):

$$V_v = (\rho_c - \rho)/\rho_c \quad (1)$$

where ρ_c is the theoretical density of the composite and ρ is the actual density, measured experimentally according to ASTM D792 [30]. The theoretical density ρ_c is calculated from the rule of mixtures, as shown in Eq. (2):

$$\rho_c = \rho_f V_f + \rho_m (1 - V_f) \quad (2)$$

where ρ_f and ρ_m are, respectively, the densities of the fiber and the matrix and are given by the technical datasheets of the materials used. V_f for the glass/epoxy composites is determined experimentally according to ASTM D2584 [31]. V_f for the carbon/epoxy composites is determined experimentally according to ASTM D3171 [32]. As mentioned in [28], although ASTM D2734 references only ASTM D 2584, the void calculation with Eq. (1) is equally applicable to method ASTM D3171.

The unnotched tensile tests are performed according to the ASTM-D3039 [33]. The OHT and FHT tests are performed according to the ASTM-D5766 and ASTM-D6742, respectively [26,27]. The PLT and BJ (one and two bolts) are performed according to ASTM-D5961 [34]. For the case of three- and four-bolt BJ's, the same geometry with two bolts (ASTM-D5961) is used, except the joint members are extended to house the third and fourth bolts with the same inter-bolt distance and end-distance. All of the mechanical tests are performed on a servo-hydraulic MTS machine model 810, as illustrated in Fig. 2, for a three-bolt, single-shear lap joint.

Table 1
Average physical properties of the VARI manufactured carbon/epoxy and glass/epoxy laminates investigated. STD: standard deviation, V_f: fiber volume fraction and V_v: void volume fraction.

Laminate	Average thickness	STD	Average V_f	STD	Average V_v	STD
	mm	mm	%	%	%	%
Carbon/epoxy	2.65	0.04	53.20	1.30	1.31	0.29
Glass/epoxy	2.75	0.03	51.16	1.24	0.71	0.18

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