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Experimental and numerical analysis of the mechanical behavior of composite-to-titanium bolted joints with liquid shim

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1. Introduction

Modern aircraft is a high level product which makes its components and assemblies typically built to much higher precision (tolerances as small as 3×10^{-4} on a relative basis) than other industries because of the functions of the components [1,2]. Gaps usually occur at the faying surfaces during assemble different large-scale structures together, for example, the centre box and the outer wing of the commercial civil aircraft are often manufactured using different tools and need to join together finally. This problem can be exacerbated for the composite structures as it is comparably more difficult to control the geometric features of the composite parts than those of metallic ones. Pre-stress would be introduced by these gaps and the assembly forces, which would result in the development of cracks of delamination in composite material and would compromise the performance of the structure [3–5]. To avoid these problems, liquid shim was often used to fill the gaps to eliminate the possible pre-stress introduced by the assembly force [6].

Some specifications [7–11] and patents [12–15] were published to guide the application of shims. However, the knowledge about the usage of liquid shim on the structural integrity of composite structures is still limited, which causes cracks in composite skin on the last generation of airliners (B787 and A380) [16]. To investigate the influences of liquid shims on the joint performance, Comer et al. [17] experimentally studied the influences of thermal and mechanical-fatigue loading on the life of composite–aluminum hybrid joint with liquid–shim, but no significant degradation of the liquid–shim in terms of a loss of mechanical stiffness was observed. Huhne et al. [18] carried out quasi-static tests to investigate the influence of liquid–shim thickness on the strength and structural behavior of carbon fiber laminate single-bolt joints, and they found the joint stiffness reduced with shim thickness but ultimate joint load was unaffected up to a liquid–shim thickness of 1.5 mm. However, Mil-Handbook [19] hold different point of view: it states the usage of shims will cause reduction of bearing strength in bolted composite joints even if the shim is very thin, and as the thickness of the shim increases, the reduction will be greater.

From all above, it can be seen that most investigations were based on experiences and tests, and the influence of only a few discrete shim thickness values were given due to the cost of the experimental test. Furthermore, it is difficult to discover the mechanism behind the phenomena just according to test method. For this purpose, this paper both experimentally and numerically studied the effects of the usage of liquid shim on the mechanical behavior of the composite-to-titanium bolted joints and the achievements will be beneficial for optimizing the usage of liquid shim in assembly.

2. Experimental procedure

2.1. Specimen description

Three batches of composite-to-titanium hybrid joints with the same geometry configurations and materials but different shimming conditions (without shim, with 0.5 mm thick liquid shim and with 1 mm thick liquid shim) are tested. The joint with 1 mm thick shim is shown in Fig. 1. Six sets of hi-shear fasteners are used to connect the two plates together and each set of HST fasteners is

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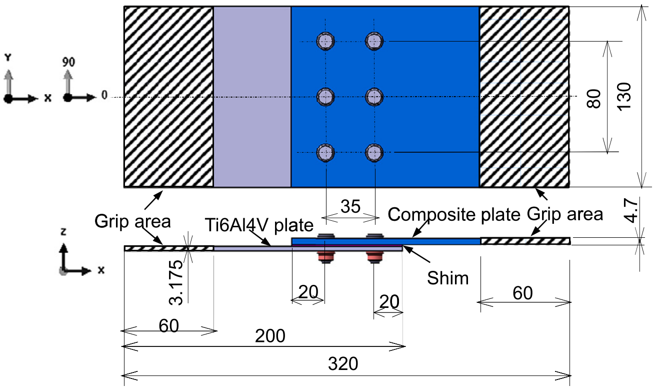

Fig. 1. Specimen geometry dimensions (all dimensions in mm).

Fig. 2. Test setup.

composed of one HST12AP10 protruding tension head HI-LITE pin and one HST1087-10 A-286 HI-LITE collar.

The metallic plate is made of annealed titanium alloy, Ti6Al4V. The material of the liquid shim is Henkel Hysol EA9394, which is an aluminium powder-filled, amine-cured epoxy based two-part structural adhesive paste that cures at room temperature. The tensile modulus of the Hysol EA9394 is 4237 MPa, the shear modulus 1461 MPa, the elastic limit 60 MPa, the ultimate strength 184 MPa and the ultimate tensile elongation 0.289 [20,21]. The composite plate is made of CYCOM carbon fiber/epoxy composite laminate, whose nominal cured ply thickness is 0.188 mm and stacking sequence is [±45/0/0/±45/0/0/±45/±45/90/±45/±45/0/0/±45/0/0/±45]. The 0° direction of the laminate is coincident with the principal load direction, which means the "1" (longitudinal), "2" (transverse) and "3" (through-the-thickness) directions of the unidirectional tape lamina with 0° are coincident with the "X", "Y", and "Z" directions of the coordinate system shown in Fig. 1, respectively. The mechanical properties of the unidirectional tape lamina are shown in Table 1. Because the thickness properties of the composite are very difficult to obtain, it is customarily assumed that the matrix properties apply in the thickness direction [22]. Therefore, it can be said that $E_{22} = E_{33}$, $G_{12} = G_{13}$, $\upsilon_{12} = \upsilon_{13}$, $S_{22} = S_{33}$ and $S_{12} = S_{13}$ apply for the unidirectional lamina.

In Table 1, the E_{ij} $(i, j = 1, 2)$ are the elastic modulus of the unidirectional tape lamina in longitude and transverse directions. The G_{ij} $(i, j = 1, 2, 3)$ are the shear modulus, the υ_{ij} $(i, j = 1, 2, 3)$ are the Poisson's ratios, and the S_{ij} $(i, j = 1, 2, 3)$ are the material strengths. The superscripts T and C denote tension and compression, respectively.

2.2. Experimental test

All specimens were tensioned using a MTS Landmark electron–hydraulic servo-controlled material testing machine (MTS-SANS 5305) in accordance with the American Society for Testing and Materials D5961 [23], as shown in Fig. 2. Five repeated tests were conducted for each type of specimens. The specimens were connected to the two heads of the testing machine via a set of steel jig. The stationary head of the testing machine was fixed while the movable head can move along the up-and-down direction. After the specimens were centre-aligned according to the strain data, they were tensioned quasi-statically at a constant cross-head speed of 2 mm/min to eliminate the dynamic effect. The load and displacement were measured with a built-in load cell and displacement transducer of the testing machine. The data were recorded at a sampling rate of 10 data per second. The temperature was maintained to be with 23 ± 5 degree Celsius and the relative humidity was within 55 ± 5% during the tests.

3. Numerical simulation

3.1. Meshes and boundary conditions

A nonlinear three-dimensional finite element model was constructed using the commercial finite element code, Abaqus/standard [24] as shown in Fig. 3. Considering the symmetric features of the structure, materials, constraints, and loading conditions, just half of the joint was modeled to decrease the computing time. Since the nut and fastener shank were engaged together, they were modeled as one part to decrease the contact surfaces and ensued shorter processing time. The "surface-to-surface contact pair" method was used to define the contact relationships in the joints. The penalty and "hard" contact methods were used to define the tangential behaviors and normal behaviors of all contact pairs.

To avoid the shear locking problem, more accurately simulate the bending deformation introduced by the secondary bending effect, and decrease the computing time, reduced linear eight-node three-dimensional solid elements, C3D8R, were used to model each ply of the laminate and the metallic plate and fasteners. The meshes in the areas covered by the fastener head and nut were refined to be six elements distributing along the radial direction and 40 elements along circumferential direction. The modeling method of one element for per ply can provide a reasonable approximation of the through-thickness stresses. Liquid shim layer was also meshed as C3D8R elements and these elements have coincided nodes with the elements representing the composite plate because the liquid shim adheres to the composite plate. The 0.5 mm thick liquid shim was modeled by two layers of elements with equal thickness and the 1 mm thick liquid shim was modeled by four layers of elements. Figs. 3(b), (c) and (d) are the detail views of "A" in Fig. 3(a) for the joints without shim, with 0.5 mm thick shim and with 1 mm thick shim, respectively.

The boundary conditions of the finite element model are shown in Fig. 3(a). The symmetric surfaces of the two joint plates and

Table 1
Mechanical properties of the unidirectional tape lamina.

Elastic property	E_{11} (GPa)	E_{22} (GPa)	G_{12} (GPa)	G_{23} (GPa)	υ_{12}	υ_{23}
Value	175	8.03	4370	2875	0.32	0.4
Strength property	S_{11}^T (MPa)	S_{11}^C (MPa)	S_{22}^T (MPa)	S_{22}^C (MPa)	S_{12} (MPa)	S_{23} (MPa)
Value	2786	1602	86.4	212.8	111.9	36.5