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Combined and interactive effects of interference fit and preloads on composite joints

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Abstract The combined and interactive effects of the bolt-hole fit conditions and the preloads of the fasteners on the load carrying capacity of single-lap composite-to-titanium bolted joints have been investigated both experimentally and numerically. Quasi-static tests of the hybrid joints with different fit conditions are implemented, and a three dimensional finite element progressive failure analysis model is proposed to predict the influences of the bolt-hole fit conditions and fastener's preloads on the mechanical behaviors of the joints. Based on the experimental validated simulation method, a multi-factor, mixed levels orthogonal design table and the analysis of variance method are used to arrange the simulation conditions and to further study the interactive effects of preloads and fit conditions. Through the analysis of the results, for the researched double bolt, single-lap composite-titanium joints, it is found that: the effects of both the interference fit and the preloads change from positive into negative mode with the increase of the interference fit values or preload values; appropriate bolt-hole fit conditions and preloads can improve the bolt-hole contact conditions of the loaded joints, and then retard the fiber failures around the fastener holes, and increase the load carrying capacity of the joints eventually; the interactive effect of the bolt-hole interference fit conditions and preloads cannot be ignored and the parameters need to be considered together and synthetically as the joints are being optimized.

1. Introduction

Composite materials are increasingly utilized in aviation structures due to their comparatively high specific strength and stiffness and the potentiality of reducing energy consumption.[1,2] Although the application of composite materials increases the integrity of aircraft structures, many composite components still need be joined to other components through bonding, mechanical fastening or hybrid of them. Among these methods, bolted joint is the most favorite one because it is relatively more reliable to transfer higher loads, easier to assemble and disassemble, more tolerant to environmental damages, and helpful in preventing interlamination.[3–5] However, the enhanced stress concentration around the fastener hole often decreases the load carrying capacity of the composite structures.[6] Comparing with the metallic structures, joining technology in the composite laminate structures is a significant issue with 60%–85% of failures occurring at the fastening joint.[7] In order to increase

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the load carrying capacity of the composite mechanical joints, a large quantity of parametric studies have already been performed, and it can be concluded that the joint strength is influenced not only by joint geometries, joint configurations, material parameters and loading condition, but also by the assembly factors such as the preloads of the bolts and the fit conditions between the fastener shank and the hole.[8,9]

In the past, the fit conditions between the fasteners and plates are normally clearance fit, with 0.1 mm typical clearance in aircraft joints.[8] However, the formerly Mcdonnel Douglas Corporation has stated that interference-fit joining can improve the fatigue life of carbon epoxy composites.[7,10] Other researchers have also concluded that the interference-fit joining will not only influence the load sharing between the multiple fasteners[11], but also improve the static strength and fatigue strength of bolted joints.[12–14] Whereas, excessive interference fit between the fastener shank and hole will produce interlaminar shearing stress and cause delamination around the hole boundary, and then decrease the joint strength.[15,16] Therefore, an appropriate interference fit value is needed for specific composite joint structures.

Tightening torque will bring clamping force and lateral constraint to the area covered by the fastener head or nut, and the beneficial effect of clamping forces/preload on the bearing strength of composite has been studied extensively. Sen et al.,[6] Khashaba et al.,[8] Cooper and Turvey[17] and Rosales-Iriarte et al.[18] all have performed experimental researches on the influences of the tightening torque on the mechanical behaviors of composite joints. Sun et al.[19] have numerically investigated the lateral constraining effect on bolted composite joints using ABAQUS software. In these studies, all of the researchers have found the bearing strength of bolted joint improves with the increase of tightening torque in a range for the specified joint configurations. However, it is well known that laminate composite structures have poor properties in the through-the-thickness (TTT) direction and are susceptible to damage and failure because the properties in the TTT direction is comparatively matrix-dominated. Thus, the composite components may fail in advance if the clamping force of the bolts is too big.[6] NASA Marshall Space Flight Center has developed an in-house standard, MSFC-STD-486B, to specify tightening torque values of the threaded fastener joint, and it is recommended that the bolt preload should be less than 30% of the fastener yield strength for typical preloaded composite structural assemblies in tension.[20] Thomas and Zhao[21] have tested the single plain composite plate made of graphite/epoxy with different thicknesses and bolt diameters and found that preload limits as specified by MSFC-STD-486B are acceptable. Nevertheless, the preload values above are directly related to the tension property of the fastener and consider neither the difference among the properties of different composite structural members in the TTT direction, nor the secondary bending effect in single-lap joints which will also introduce out-of-plane stress in the region surrounding the fastener hole. Therefore, the preload may also lead to both positive and negative effects. The positive effect is that, as the preload is increased, the friction forces between the joint members become higher and the lateral constraint introduced by the tightening torque will suppress the local delamination to be onset and progress to some extent, and then the load carrying capacity will grow. On the other hand, the negative mode effect is that too high out-of-plane stresses introduced by the preload can lead to a premature failure of the joint.[22,23] Therefore, an appropriate preload value is needed for specific composite joint structures.

From all the above-mentioned descriptions and analyses, it can be seen that both the bolt-hole fit conditions and preloads of the fasteners affect the joint behaviors through changing the stress state surrounding the fastener hole, and the effects of both the fit condition and the preload have been investigated a lot separately in the past studies. Nevertheless, the optimized values of them have not been founded in these researches. Moreover, unlike laboratory studies, the practical joint strength is affected by lot of different parameters simultaneously. That is to say the effects of both the fit conditions and preloads may impact each other, and the optimized preload of the composite joint with a certain bolt-hole fit condition may no longer the best for the similar joints with other fit conditions, and vice versa. However, the interaction of them has received little attention up to now. Consequently, the main objective of the present work is to investigate the combined and interactive effects of bolt-hole interference fit conditions and preloads of the fasteners on the load carrying capacities of the single-lap composite joints, and to optimize the parameter of the joints. Experimental test method, three-dimensional finite element method and analysis of variance (ANOVA) method will be synthetically applied in the following study.

2. Problem statements

Two typical composite-to-titanium, two-bolt, single-lap joints with the same configurations other than the bolt-hole fit conditions will be used in this study, and the geometry and dimensions of the joints are shown in Fig. 1, in which the locations and dimensions tolerances conform to the general tolerance requirements for composite products HB 7741-2004. Both the composite plate and titanium plate are 210 mm long, with 60 mm griping length. The thicknesses of the composite plate and titanium plate are 3.8 mm and 2 mm, respectively. The two plates are joined together by two HST10AP6 hi-lite fasteners, and the diameter of the fastener shank is 4.8 mm with tolerance being ±0.013 mm. The diameters of the fastener holes of the two different joints are $4.8_{0}^{+0.01}$ mm and $4.8_{-0.1}^{-0.04}$ mm, respectively. Thus, the fit conditions between the fastener shanks and holes of the two different kinds of joints can be seen neat fit and 1.5% interference fit, respectively.

The materials of the titanium plate and the two HST10AP6 hi-lite fasteners are both Ti6Al4V titanium alloy manufactured per AMS 4967. Its elastic modulus is 110000 GPa and Poisson ratio is 0.34. The material of the composite plate is a hybrid material manufactured from unidirectional tape lamina (CYCOM 977-2-35%-12KHTS-134-300 of Cytec Industries Inc.) and twill woven carbon fabric composite (CYCOM 977-2A-37%-3KHTA-5HS-280-1200 of Cytec Industries Inc.) with stacking sequence being $[(\pm45)/0/\pm18/\pm36/+54/(0/90)/-54/\pm72/90]_s$. In the stacking sequence, the angle value, such as +54, represents the unidirectional tape lamina with its fiber direction shifting 54° from the 0° direction shown in Fig. 1, and (angle value), such as (±45), represents the woven fabric with its warp direction shifting 45° from the 0° direction shown in Fig. 1. The material system of the laminate coincides with the geometry coordinate system of the specimen, which means the 1, 2 and 3 directions of the unidirectional tape