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Effect of Liquid Shim on the Stiffness and Strength of the Composite-composite Single Lap Joint

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Abstract. The problem of assembly gap is gradually exposed due to the low assembly precision of the composite component. This paper takes the composite-composite single lap joint with Hi-lock bolt as the research object, the influence of the liquid shim on the mechanical properties of the composite joints was studied. The stiffness and the maximum load of the composite joints decreased with the increase in the thickness of the liquid shim layer. The introduction of the liquid shim layer enlarges the geometric eccentricity of the load path and makes the problem of the uneven contact between the bolt and the inner surface of hole more serious. The radial stress of the compression zone between the hole and bolt increases significantly with the increase in the thickness of the liquid shim layer.

Introduction

The problem of assembly gap is gradually revealed with the widespread application of composite materials. Actually, it is inevitable to introduce the assembly gap between the mating surfaces in the process of aircraft assembly no matter the parts are comprised of metal or composite material. Furthermore, low manufacturing accuracy of composite materials due to the complexity of the manufacturing process exacerbates the problem of assembly gaps. Once the assembly gaps between the mating surface are excessive, it is necessary to adopt gap-filling measures rather than to eliminate the gap by the bolt clamping force, otherwise the delamination, cracks or other damage inside the composite material would be produced [1].

In order to prevent the composite cracks and delamination, liquid shim is appropriate where the gap to be shimmed is tapered or variable in height as they can conform to the surface profile of the mating components. Formulations have been developed to fill gaps in the range 0.127-0.762mm. If the gap is more than 0.762mm (0.03 inches), it is necessary to introduce solid shim at the scope of engineering required[2][3]. J.X. Dhôte et al.[4] studied the influence of a liquid-shim layer in place at the interface between the two laminates of single-lap joints by analyzing surface strain field which is provided by three-dimensional Digital Image Correlation (DIC).Liquid shim layer modifies the strain distribution, potentially leading to higher tensile strains in the laminates. L Liu [5] studied the influence of liquid shim layer thickness on the mechanical behaviors of composite-to-titanium bolted joints, and it can be concluded that the maximum load, initial joint stiffness and design load of the joints decrease with the increase of liquid shim layer's thickness.

The main question discussed in this paper is the effect of liquid shim layer on mechanical behavior of the single lap, composite-to-composite joint. Most of those researches related to the gap-filling problem were carried out in the type of composite-to-metal joint, so one important purpose of this article is to prove that whether the liquid shim layer still has the same effect on the composite-to-composite joint as the composite-to-metal joint.

Experimental Procedure

The setting of experimental groups is mainly based on the suggestions given in the literature, and the range of shim layer thickness is extended. Four cases including 0.2mm, 0.4mm, 0.6mm, 0.8mm were chosen to complete the experiment and FEM analysis.

As shown in Figure 1, the specimens are single-lap joints consisted of carbon/epoxy laminates. The Hi-Lite HST10 with protruding shear head and hi-lock collar HST79 were used.

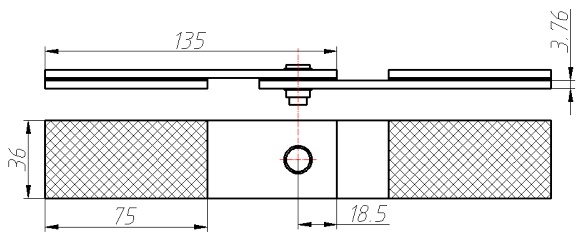

Figure 1. Geometry of the specimen.

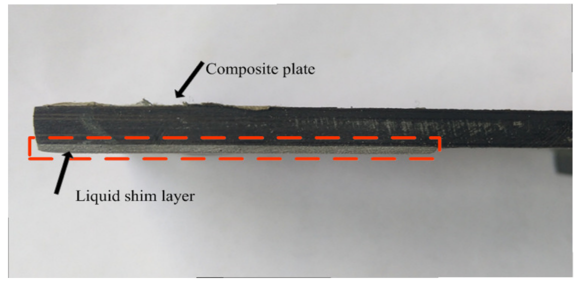

Figure 2. Liquid shim layer.

All of the specimens are made of CYCOM 977-2-35-24K/IMS-194 , whose nominal cured ply thickness is 0.188mm and stacking sequence is [+45/90/-45/0/90/0/-45/90/+45/-45]s. The second generation liquid shim EA9394 was adopted. Hysol EA9394 is a two-part structural paste adhesive that includes amine-cured epoxy adhesive and aluminum powder filler. It is widely used due to thixotropic nature prior to cure and excellent high temperature compressive strength[6].The weight part ratio between resin and hardening agent is 100:17 and it needs room temperature curing for 120~168 hours[7]. The cured liquid shim is shown in Figure 2.

The single-bolt specimens were tested in tension in a 100 kN tensile test machine with a constant crosshead displacement rate of 2 mm/min. The load-displacement curve of the specimen was achieved by experiment , and loading stopped when excessive displacement occurred after the peak load. The load value can be picked up directly from the tensile test machine. extensometer was adopted and the feet were placed symmetrically about the centric line of the hole.

Numerical Simulation

Table 1. Material Constants of CYCOM 977-2-35-24K/IMS-194.

Longitudinal modulus, E1 (GPa)	156	Longitudinal tensile strength, XT (MPa)	2500
Transverse modulus, E2 (GPa)	8.35	Longitudinal compressive strength, Xc (MPa)	1400
Transverse modulus, E3 (GPa)	8.35	Transverse tensile strength, YT (MPa)	75
In-plane shear modulus, G12 (GPa)	4.2	Transverse compressive strength, Yc (MPa)	250
Out-of-plane shear modulus, G13 (GPa)	4.2	Longitudinal tensile strength, ZT (MPa)	75
Out-of-plane shear modulus, G23 (GPa)	2.52	In-plane shear strength, S12 (MPa)	95
Major Poisson's ratio, $\mu12$	0.33	In-plane shear strength, S13 (MPa)	95
Through thickness Poisson's ratio, $\mu13$	0.33	Out-of-plane shear strength, S23 (MPa)	108
Through thickness Poisson's ratio, $\mu23$	0.55		

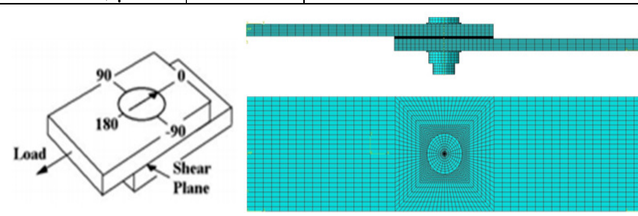

Figure 3. The FE model.

Table 2. Elasto-plastic Properties of Ti–6Al–4V[8].

	σ_y	ε_p
yield stress, σ_y (MPa) plastic strain, ε_p	950	0
	1034	0.002
	1103	0.1

The progressive damage analysis is introduced to consider the non-linear stress–strain relationship of composite material. The three-dimensional initial parameters of the composite properties are shown in the table1. The failure criterion used in this paper is a modified version based on the original failure criterion which is proposed by Olmedo and Santiuste, and it is an extension of Chang–Chang and Chang–Lessard criteria considering the out-of-plane stresses [9]. Fiber tensile criteria include shear terms in the original failure criterion. However, the original fiber tensile criterion was replaced by the maximum stress criterion during the analysis process. There is a comparison result between Hashin failure criteria and the maximum stress, the former contains a shear term while the latter is not. In cases where the shear stress is small compared to the tensile longitudinal stress, both of the criteria gives similar results. However, when the shear stress is large, Hashin failure criteria is much more conservative than the maximum stress criteria[10].To overcome this difficulty, replace the original fiber tensile criteria with the maximum stress criteria. The influence of shear nonlinearity is considered in the original criterion. The effect of shear nonlinearity on the prediction results depends on the shop floor angle. The predicted bearing stress-displacement relationship for the $[0/90]_S$ laminate is more accurate when considering the effect of shear non-linearity, while the predicted strength for the $[(\pm45)6]_S$ laminate is increased a lot when the shear behavior is non-linear. As for the quasi-isotropic $[(0/\pm45/90)3]_S$ laminate, non-linear shear behavior has a slight effect on the results[10].So, it is not necessary to consider shear nonlinearity in the criterion for the laminated plates used in current study. The failure criteria were implemented using user subroutine USDFLD. The material of bolt is Ti6Al4V. The mechanical properties of the material are presented in the table1,2.

Comparison of Numerical Results with Experimental Data

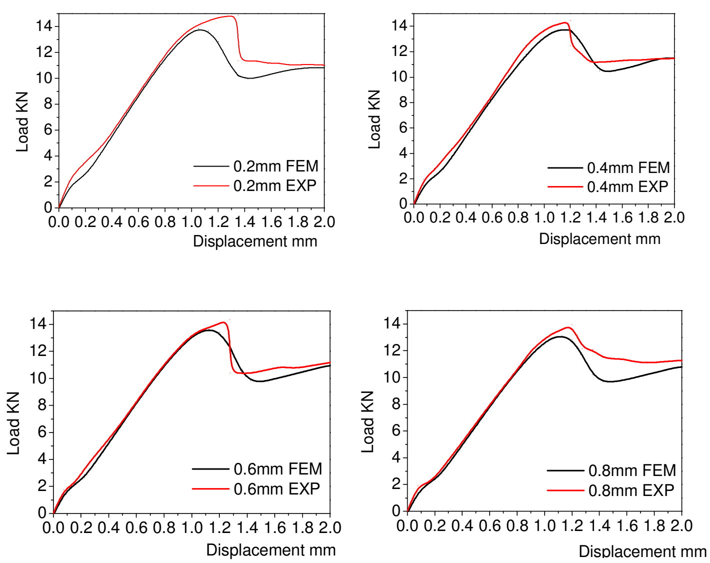

Figure 4. Load-displacement curve.

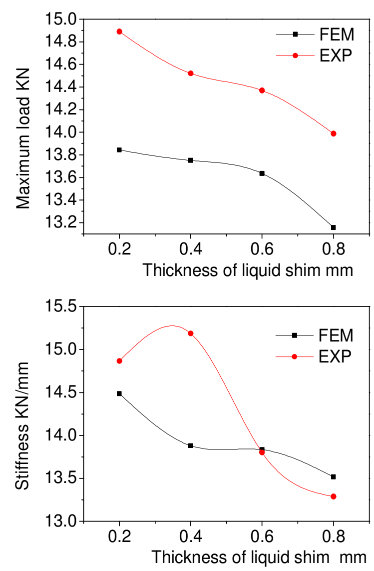

Figure 5. Maximum load and the stiffness of the joints.

The load-displacement curves of both the experiment and numerical simulation containing different thickness of the liquid shim layer are shown in Figure 4. The linear segment in the middle of the curve is in good agreement with each other between the experiment and the FEM result, while the deviation of maximum load of the joints is relatively larger and simulation result tends to be conservative. The effect of the liquid shim layer on the maximum load of the joint is illustrated in Figure 5, the FEM result corresponding to the shim layer thickness of 0.2mm,0.4mm,0.6mm,0.8mm is 7.04%, 5.30%, 5.10%, 5.93% lower than the experimental results, respectively. Both the experimental result and the simulation result show that the maximum load decreased with the increase in the thickness of the liquid shim layer. In terms of the experimental results, the maximum load of the joints containing the shim layer thickness of 0.4mm,0.6mm,0.8mm decreased by 2.49%, 3.50% and 6.07% respectively compared to the joint containing the 0.2mm liquid shim layer.

The stiffness of the joint is calculated from the linear segment of the load-displacement curve, as shown in Figure 5. Overall, both the experimental and numeral result show that the stiffness of the joint decreased with the increase of the thickness of the shim layer except for the experimental result containing 0.4mm shim layer, the maximum deviation between the experimental and simulation result occurs at this point, accounting for 8.60% of the corresponding experimental result. When the thickness of the shim layer increased to 0.8mm, joint stiffness of the experimental and simulation result decreased by 10.62% and 6.70% respectively, compared to the joint containing 0.2mm liquid shim layer.

Stress Analysis

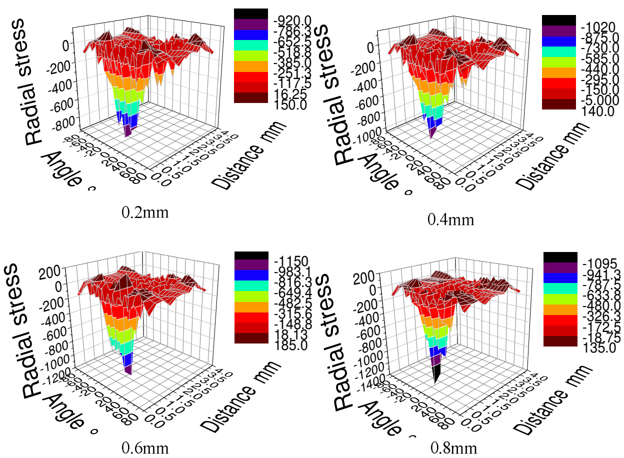

Figure 6. Radial stress distribution inner wall of the hole -300Mpa.

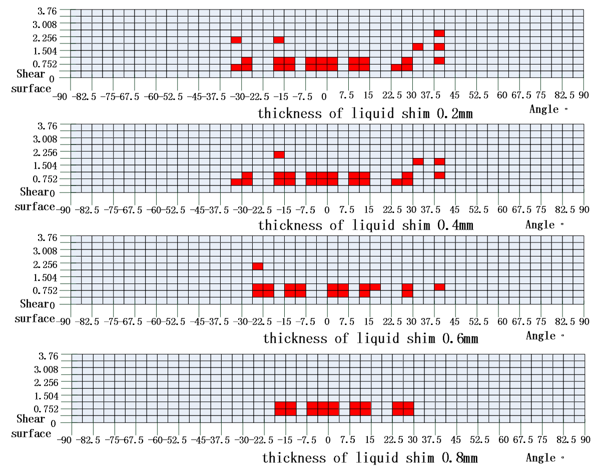

Figure 7. The region of the radial stress on the greater than -300Mpa.

To investigate the the uneven contact caused by the tilting bolt, the stresses were extracted from the integration points of the elements closest to inner face of the hole at an applied load level of 5 kN. Radial stress distribution on the inner wall of the hole is not uniform,as shown in Figure 6. The stress of the region near the shear plane , approximately in the range of -30~30 degrees is significantly higher than other regions. Obviously, the area with higher radial stress level contact with the bolt firstly during the process of tentile testing, bearing the primary load. The stress level of this region increases with the increase in the thickness of the shim layer. In order to show the location of the area with higher radial stress, the contact area between the bolt and inner wall of the hole is expanded into a plane,as shown in Figure 7.

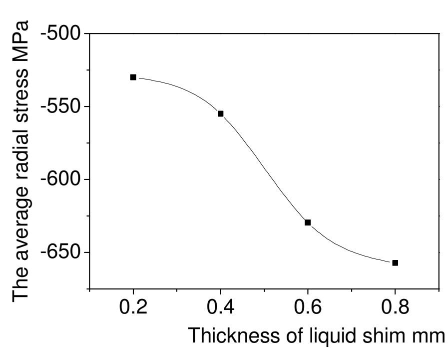

Figure 8. The average radial stress of red area.

The elements where the radial stress of the integration points is greater than -300Mpa are highlighted. With the increase in thickness of the shim layer, there is a significant decrease in the number of red elements. The distribution region is gradually shrinking to the center line and the shear plane. The average radial stress in the red region is calculated, respectively, as shown in Figure 8. The initial positions of the three damage modes are all located in the high radial stress region,as shown in Figure 9, the red circle mark.

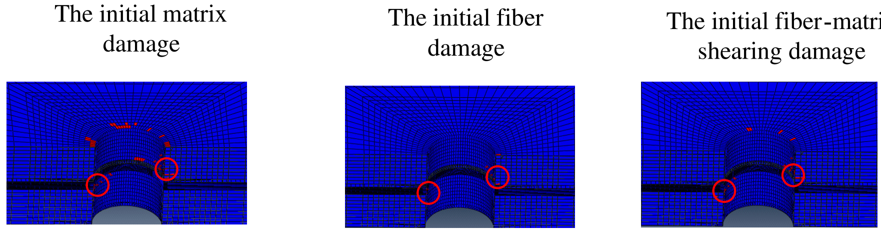

Figure 9. The initial positions of the three damage modes.

It can be known that the average radial stress of the red area increases with the increase in thickness of the shim layer. When the thickness of the shim layer increases to 0.8mm, the average radial stress is 24.01% higher than the model with 0.2mm shim layer. The shrinkage of the red area and the increase of the average radial stress indicate that the introduction of shim layer increases the concentration of contact force between the bolt and inner wall of the hole and this problem is becoming more and more serious with the increase in thickness of shim layer.

The introduction of liquid shim increases the distance between the two spacemens and then amplifies bending moment of the single-lap joint at last.We could draw the conclusion that the liquid shim layer still has a serious impact on the geometric eccentricity of the load path in spite of the small thickness of liquid shim.Higher the radial stress, greater the damage to the inner wall of the hole.So the thicker shim layer would speed up the failure of materials,and the final manifestation is the reduction of stiffness and strength of joint.

Conclusion

1) Both the stiffness and maximum load of the single lap, composite-to-composite joint decrease with the increase in the thickness of the liquid shim.

2) The radial stress distribution on the contact area is greatly influenced by the thickness of the liquid shim layer. The shrinkage of the red area and the increase of the average radial stress indicate that the introdution of shim layer increases the concentration of contact force between the bolt and inner wall of the hole,which would cause the reduction of stiffnes and strength of joint.

Acknowledgement

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