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INVESTIGATING MECHANICAL PERFORMANCES OF DOUBLE LAP COMPOSITE JOINT WITH STEPWISE PATCH

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ABSTRACT

An adhesive-bonded double-lap composites joint with stepwise attachments was proposed and investigated experimentally and numerically in this study. For the conventional double lap joint (DLJ), the high shear stress and peer stress taking place in the adhesive layer near the patch termination significantly influenced the joint strength. In order to diminish the amount of the stresses, a new design of stepwise patch was introduced in the fabrication of the double-lap joint. Based on the finite element stress analysis (FEA), it was found that both shear stress and peer stress within the adhesive layer was reduced appreciably by the employment of the stepwise attachment. In addition, experimental results illustrated that the double lap joint with stepwise patch exhibited superior joint strength than the conventional double lap joints.

Keywords: Composites, Finite element stress analysis, Joint design

1. INTRODUCTION

Adhesive bonding has been an attractive method of joining composites' parts together because it can prevent the damage of the continuous fiber composites caused by mechanical fastening. Moreover, weight saving and corrosion resistances are also advantages of the adhesive joint over the traditional rivet and bolt joints. There are many different configurations of adhesive joints, among which the most commonly used are lap joints, i.e., single lap joint and double lap joint. This is because of the lap joints being quite simple and manufactured easily with low cost. However, the joint strength as well as the load carrying capacity of the lap joints are always significantly affected by the high peer stress and shear stress generated within the bonding layer. Therefore, the main design tasks of lap joints are toward the reduction/prevention of local stress concentration. In past decades, several designs with the modification of the lap configuration were proposed to improve the load bearing capacity of the lap joints. A wavy-lap joint was proposed to replace the conventional flat-lap bonded joint such that the peel stresses that should be tensile in the conventional flat joint become compressive near the joint ends (Zeng and Sun 2001). With the compressive normal stress, the wavy-lap joint exhibits the superior tensile strength as well as the

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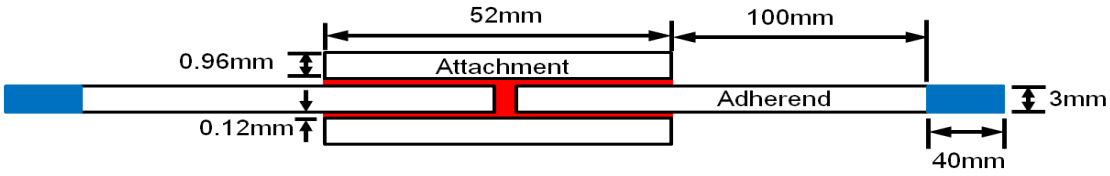
longer fatigue performance than the conventional one (Zeng and Sun 2004). Recently, Ashrafi et al. proposed a single lap joint with sinusoidal bonding surfaces (Ashrafi et al. 2012). Results indicated that the specimens with the non-flat interface (A/H=0.4) have a 40% higher failure load than the conventional flat joint. To eliminate the bending caused by the eccentricity within the single lap flat joint, Kishore and Prasad introduced the design of flat-joggle-flat bonded joint (Kishore and Prasad 2012). It was found that the failure load of the new design joint is increased up to 90%. Rather than the modification of lap configuration, the interadherent glass fiber going through the composite adherents was introduced by Beylergil et al. to increase the interfacial strength of the single lap joint (Beylergil et al. 2011). Around 80% enhancement of the tensile strength was obtained in their experiments. In the past, efforts were made to enhance the mechanical performance of the single lap joints; however, few studies concerning the new designs of double lap joint were reported. In general, double lap joint (DLJ) without the attributes of eccentricity demonstrates higher strength than single lap joint. Lee et al. compared the joint strength of double lap joint and supported single lap joint, indicating that the double lap joint provides better performance than the single lap joint (Lee et al. 2009). A similar tendency was also observed by Taib et al. (Taib et al. 2006). Choupani characterized the effect of joint configuration as well as the adhesive thickness on the strength of the adhesively bonded double lap joints by means of the finite element analysis (Choupani 2009). Based on the fracture mechanics and the stress analysis in the bonding layer, the factors influencing the strain energy release rate and the stress concentration in the double lap joint were discussed. Cheuk et al. proposed an analytical model to investigate the crack propagation behaviors in metal-to-metal double lap joint under fatigue loading (Cheuk et al. 2005). The energy release rate calculated based on their analytical model was correlated well with the finite element analysis. A comprehensive review of adhesively bonded joints in terms of finite element analysis can be found elsewhere (He 2011). In light of forgoing investigations, the stress distributions of double lap joint associated with adhesive thickness and adhesive properties were mainly of concern; however, the novel design of the double lap joint for the improvement of joint strength is scarce in literature. If a new design of double lap joint with notable performance can be accomplished, the adhesively bonded joint can be extensively employed in bonding the composite structures with reliability and safety. In this study, the double lap joint with a new design of stepwise attachments was proposed and then validated by simple tensile tests and fatigue tests. Meanwhile, a 2-D finite element analysis was performed to elaborate the stress distribution within the adhesive layer of the new design double lap joint. The numerical results correlated with the experimental data were utilized to elucidate the advantage of the stepwise attachment on the enhancement of the mechanical performance of the double lap joints.

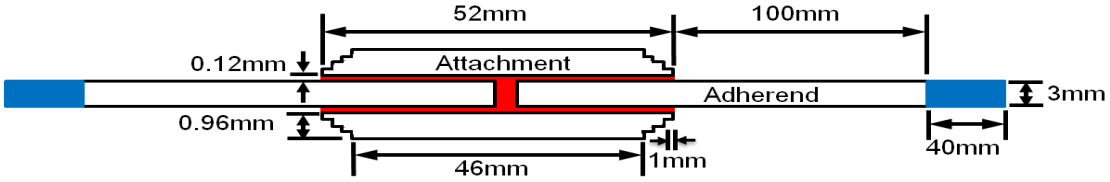
2. DESIGN OF ADHESIVE JOINT

The double lap joint with stepwise attachments was introduced and experimentally investigated. For reference purposes, the conventional double lap joint was also included in the investigation.

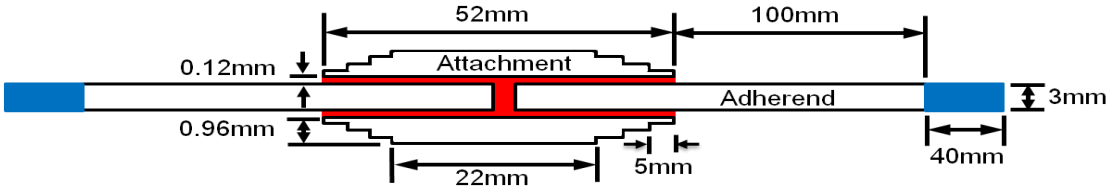
The basic geometric configurations of the joints accounted for in the study are shown in Fig. 1. Fig. 1 (a) indicates the conventional double lap joint, and for simplicity, it is denoted as DLJ. There are two different stepwise patched double lap joints in which the steps in the attachments are 1 mm and 5 mm respectively as shown in Figs. 1 (b) and (c). These two stepwise joints are respectively indicated as SDLJ-1 and SDLJ-2. The gap between the two adherents in the joints is 2 mm, and the width of the samples is 25 mm. The bonding areas in the three joints are designed to be the same so that the effect of the attachment can be fully illustrated. The adherent was fabricated by graphite/epoxy composite laminates with the stacking sequence of $[0_2/90_2/0_3/90_2/0]_s$, and the attachment is made by graphite/epoxy unidirectional laminates of $[0]_8$. It is noted that in the description of the above layup sequence, the coordinate system is set coincided to the loading direction.



(a)



(b)



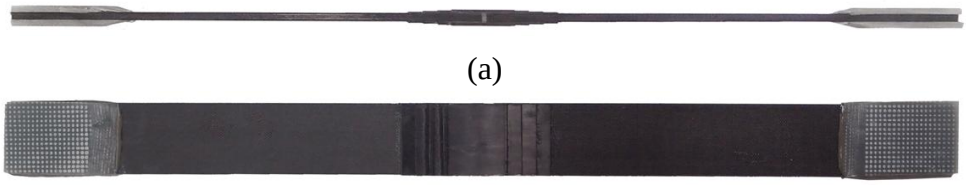
(c)

Fig. 1 Design of double lap joint ((a) conventional joint (DLJ), (b) stepwise patch joint (SDLJ-1) (c) stepwise patch joint (SDLJ-2)

3. FABRICATION AND EXPERIMENTS

The unidirectional graphite/epoxy prepreg, provided by FTC Group Taiwan, was cut to the proper dimensions and then laid up manually in accordance with the designed stacking sequence. Autoclave curing was conducted on the laminates with the recommended curing process. The adherents with the desired dimension were cut from the composites panels using a water jet. Similarly, the attachments for the DLJ samples were prepared from the 8-ply unidirectional

composite panel. On the other hand, for the preparation of stepwise attachments, unidirectional prepreg was stacked layer by layer on a specially designed mold and then cured in the autoclave. It can be found that although the geometric configuration of stepwise attachment is not symmetric, the bonding surfaces of the stepwise attachment obtained from the molding process are quite flat. Subsequently, the adherents and the attachment were bonded together using epoxy adhesive and cured at 60^{o}C for 4 hours. The thickness of the adhesive bonding line observed from the microscopy is around 0.12 mm. Afterward, a fiberglass end tab of 40 mm length was adhered to the specimens at both ends using epoxy glue. Fig. 2 illustrates the photos of the stepwise attached double lap joint. The material properties of graphite/epoxy composites employed in the study are tabulated in Table 1. All properties were measured in our laboratory by following the ASTM standard 3039 for tensile properties and ASTM standard 3518 for in-plane shear properties. In addition, the properties of the epoxy adhesive used for bonding the adherents and attachments are listed in Table 2.



(a)

(b)

Fig. 2 Photos of stepwise patch joint (SDLJ-2) ((a) side view, (b) top view)

Table 1 Material properties of graphite/epoxy composites

Young's modulus		Poisson's ratio	Shear modulus
E1(GPa)	E2(GPa)	ν12	G12(GPa)
138	9.65	0.28	5.6

Table 2 Material properties of epoxy adhesive

Tensile modulus	Poisson's ratio	Tensile strength
E(GPa)	ν	S(MPa)
4.4	0.4	34.9

In order to elaborate the effect of the stepwise attachment on the strength of DLJ, all specimens were tested to failure in tension. The experiments were conducted on a hydraulic MTS machine under stroke control at a displacement rate of 10^{-2} mm/s. During the tests, the displacement was measured directly from the linear variable differential transformer, and the loading histories were obtained from the load cell embedded on the loading fixture. For each case of double lap joints, five specimens were tested. Average strengths together with the standard deviation are shown in Fig. 3.

Results revealed that the double lap joint (SDLJ-2) with 5 mm step attachments exhibits superior joint strength than others. Nevertheless, for the double lap joint with the attachments of 1 mm step (SDLJ-1), the strength is little less than that of the conventional double joint (DLJ), although the difference is within the experimental variation. For the SDLJ-1 samples, because the steps in the attachment are only 1 mm, the contribution of the steps on the joint strength may not be substantial so that the strength is compatible to the traditional joint with the straight termination of attachments. On the contrary, for the SDLJ-2 samples, because the step in the attachments is 5 mm, the function of the stepwise attachment can be fully demonstrated, and the joint strength is around 50% higher than that of the conventional one. The failure surfaces of the stepwise double lap joints are shown in Fig. 4. It can be seen that there is clear epoxy adhesive left on the bonding surfaces of the attachment and adherent; therefore, the dominant failure mode can be recognized as the cohesive failure (Ebnesajjad 2008). In other words, the failure of the adhesive joints is taking place within the bonding line of epoxy adhesive. In order to understand why the attachment with 5 mm step can provide better joint strength than that with 1 mm step or straight termination, we resort the assistance of finite element stress analysis to calculate the stress distribution within the adhesive bonding line.

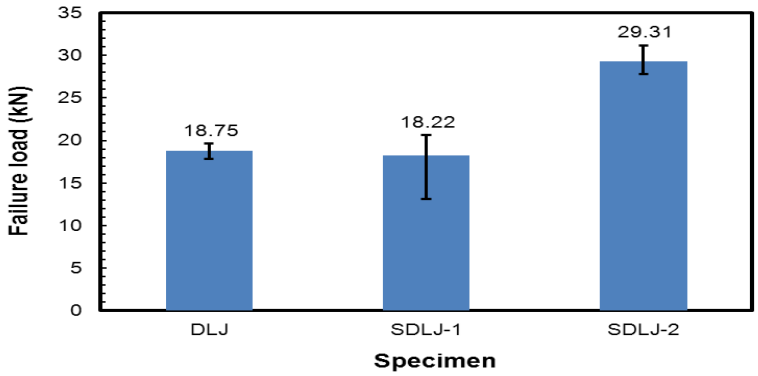


Fig. 3 Failure loads of the double lap joints.

Fig. 4 Failure surfaces of SDLJ-2 sample

4. FINITE ELEMENT STRESS ANALYSIS

In order to elucidate the experimental results, the stress distribution within an adhesive layer was analyzed using finite element analysis (FEA). Based on the geometric configuration of the specimens as well as the corresponding material properties described earlier, the finite element models for the three cases of double lap joints were generated respectively. The analysis was conducted based on the commercial code ANSYS, and plane strain element (plane 182) was utilized to model the composites laminates (adherent and attachment) as well as the epoxy adhesive. It should be noted that the nonlinear geometric deformation was accounted for in the modeling, and the materials were assumed to be linear elastic. The stress components measured from the attachment termination along the middle line of the adhesive layer were calculated, and the values were normalized with respect to the applied loading. The comparison of the normalized peel stress distribution along the adhesive is shown in Fig. 5. Apparently, SDLJ-2 exhibits the lowest stress values as well as the most uniform stress distribution within the bonding line. In addition, the SDLJ-1 sample also demonstrates lower peer stress as compared to DLJ sample. Fig. 6 shows the shear stress distributions of the three lap joints. It can be seen that SDLJ-1 and DLJ almost have the same shear stress distribution as well as the peak values. However, SDLJ-2 specimen demonstrates much lower shear stress distribution than the above two cases. Based on the stress distribution, the distribution of von Mises stress was further examined, and the results are shown in Fig. 7. The comparison reveals that the difference in von Mises stress between SDLJ-1 and DLJ samples is not substantial; nevertheless, for SDLJ-2, the corresponding value is relatively low. As a result, with the substantial reduction of peel and shear stresses within the adhesive layer, it is not surprising that the SDLJ-2 specimen can have the better joint strength. However, for SDLJ-1, the stress can be reduced by the design of stepwise attachment, yet the deduction because of the 1 mm step is too little to compensate for the experimental variations resulting from the fabrication process and mechanical testing. This is the reason why SDLJ-1 has almost the same joint strength as DLJ.

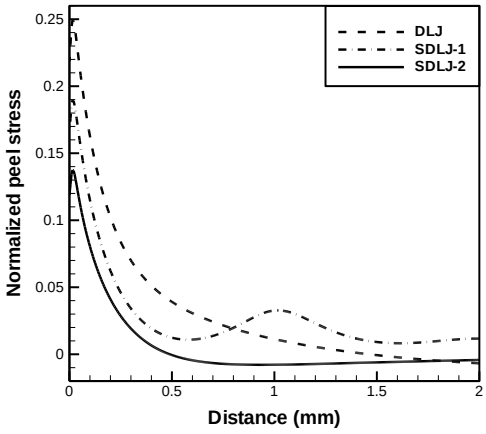


Fig. 5 Normalized peel stress distribution in the adhesive layer

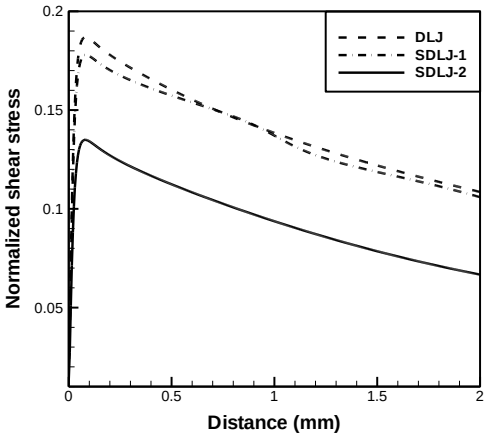


Fig. 6 Normalized shear stress distribution in the adhesive layer

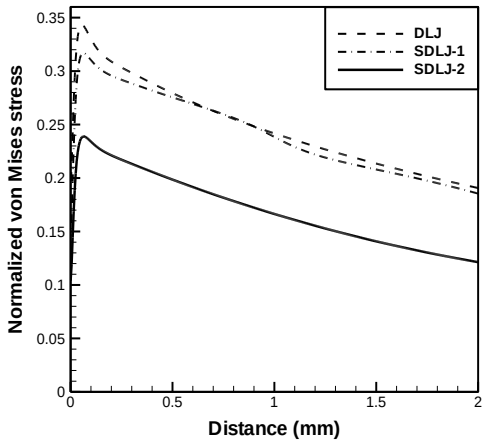


Fig. 7 Normalized von Mises stress distribution in the adhesive layer

5. CONCLUSIONS

A new design of stepwise attachment was proposed on the double lap joint, and the joint strength as well as the fatigue performance was investigated experimentally. In addition, the stress distributions within adhesive bonding line were analyzed based on FEA simulation to elaborate the function of the stepwise attachments. From the numerical simulation, it can be seen that when the designed step in the stepwise attachment is 5 mm, both the peel stress and shear stress within the double lap joint drop dramatically. On the other hand, when the step is only 1 mm, the reduction of shear stress is moderate and so is the von Mises stress such that the improvement of joint strength is limited. Currently, experimental observations validated that the double lap joint with the stepwise attachment of 5 mm steps demonstrates higher joint strength than the other two designs of joints.

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