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Improved Design for Metallic and Composite Single-Lap Joints

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In this paper, an experimental investigation of single-lap joints was carried out. A new design with attachments for efficient load transfer has been proposed. Aluminum and composite materials were used for the adherends. Irrespective of the material used, the new design is stronger than a conventional lap joint by up to about 60%. Failure modes of these joints were recorded and a finite element analysis was conducted to verify the failure modes. A detailed parametric study was conducted to investigate the effect of attachment thickness, angle of attachment, and lay-up on the ultimate strength of the joints.

Nomenclature

t = thickness of attachment
θ = angle of attachment

I. Introduction

DESPITE the development of modern technologies for manufacturing integral structural configurations, adhesive bonding remains one of the most important ways for developing and implementing innovative design concepts. It can offer substantial performance and economic advantages compared with other popular and more conventional methods of joining, especially mechanical fastening [1]. Adhesive bonding has been widely used for construction of load-bearing structural components in a great variety of industries, viz. aerospace, marine, automotive, and sports. There are many structural joining configurations that adopted adhesive bonding that have increasingly been used in the industry. Owing to its importance, extensive research was also conducted by many authors over the last few decades on adhesive joining [2–12]. Statistics show that approximately 70% of the failure of structures is initiated from joints [5]. Thus, to ensure the safety of joints in structures, it is necessary to analyze the stress distributions on the joint and design them for better efficiency.

For joints designed for in-plane load transfer, there are many varieties, including single-lap, double-lap, step-lap, scarf, strap, and other configurations. This structurally efficient way of connecting structures through shear joints has used mechanical fasteners until the advent of adhesive joining. From the literature, it can be observed that mechanical fastening can achieve only a maximum tensile strength of 50% of the weakest adherend in the joint due to the stress concentrations caused by the fastener holes, whereas adhesively bonded joints can achieve about 80% of the tensile strength of the weakest adherend [9]. This has contributed to the ever-increasing use of adhesive joining in aerospace, marine, and automotive industries.

Structural adhesives have poor resistance to normal (peel) stresses, but are adequate in shear and strong in compression. Ideally, an efficient joint design should avoid the presence of tensile peel stress along the bond line. Of all the aforementioned joint designs, the single-lap joint is generally the simplest and least expensive to manufacture. However, its intrinsic eccentricity and highly localized interfacial stresses at the ends of the lapped region make it inefficient in load transfer [2,8]. The failure often occurs at the ends of the joint due to these singular tensile normal stresses. A considerable amount of work has been done on the single-lap joint in the last few decades [1–4]. To improve the joint strength, some have suggested altering the adherend geometry to reduce the peak interfacial stresses [5,6]. Sawyer [10], and Tong et al. [11] showed that significant improvements in static loads can be obtained by transverse stitching of adhesively bonded joints. Mazumdar and Mallick [12] have experimentally investigated the effects of recessing (a concept in which the adhesive layer is placed at regular intervals, instead of as a continuous layer) on the failure load of single-lap joints. They showed that the average strength of the bond increases with recessing. Zeng and Sun [13] designed a wavy configuration in the joint region to achieve a compressive peel stress in a single-lap joint with the result of significantly increasing both the static and fatigue strengths. Coates and Armanios [14] showed in their investigation that by increasing the number of planes that transfer load, the strengths can be increased.

Analytical modeling and finite element analyses have been performed to analyze the stress/strain distributions in the adhesive and adherends [15,16]. Quasi-static failure mechanisms and strength have been investigated [17,18]. Methods have been developed and used in the designs of single- and double-lap joints, step-lap joints, and scarf joints [19].

Recently, Turaga and Sun [20] proposed a new design concept involving the use of attachments for aluminum single-lap joints. In the present investigation, that design concept of adding thin structural attachments to the joint region has been investigated in detail for two different materials. The function of the attachment is to increase the load transfer locations and thus minimize the level of interfacial stresses. It turns out that the attachment in fact makes the interfacial stresses along the original bond line compressive. Both aluminum and composite adherends have been considered owing due to their different behavior and failure modes.

II. New Design

With the aim of avoiding the high-tensile peel stress distributions at the ends of the lapped region in the single-lap joint, a new single-lap joint with attachments shown in Fig. 1 was proposed. The addition of attachments on both sides of the lapped region is intended to divert some amount of load away from the main lapped region, thus reducing the level of interfacial stresses in that region. The basic idea is to increase the number of locations that transfer the load, and thereby the load transferred at each location is reduced. It turns out that placing the attachments on top of the original (main) lapped

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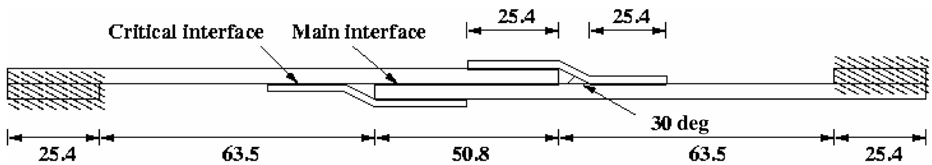

Fig. 1 Geometry and dimensions of the single-lap joint with attachment.

region, as shown in Fig. 1, can yield an additional benefit in changing the peel stress from tensile stress to compressive stress. In this study, two materials have been considered for the adhesive joint, namely aluminum and composite. Both types of joints have been investigated in detail.

III. Aluminum Joints

The attachments were taken to be 25.4 mm in length and the thickness one-fourth of the adherend thickness. The effect of varying these parameters is discussed later. Initially, an angle of 30 deg was considered to validate the concept. The geometry and dimensions of the single-lap joint with attachments is shown in Fig. 1.

Aluminum 7075 was used for manufacturing the joint adherends and attachments. It was cut to the required dimensions and the attachments were made initially with an angle of 30 deg. The attachment was made using an aluminum mold of same shape. Because surface preparation is critical in adhesive joining, the surfaces to be bonded were degreased with acetone solution and then sanded with 320 grit sandpaper to make the surface rough. The surfaces were again cleaned with acetone solution and then with distilled water. A 1% silane solution was applied to the surfaces and allowed to dry before bonding. It is recommended that the joints are dried completely to remove all moisture by keeping them in an oven at a temperature of about 100–200°C for about 1–2 h. An adhesive film FM73M was used for bonding and the joint was cured in the autoclave using the standard cure cycle for FM73M.

A single panel of about 304.8 mm wide was used to make the joints, and then the joined panel was cut into joints of 25.4 mm width. The premade attachments of 25.4 mm width were then bonded to the single-lap joints using the same procedure of surface preparation and curing.

IV. Composite Joints

S2/8552 glass/epoxy composite material was used to make the adherends and attachments for composite single-lap joints. Flat $[0/90/0/90]_{4s}$ laminates were cured in an autoclave first and then cut into adherends of width 25.4 mm. The attachments were of $[0]_{12}$ lay-up. A specially made aluminum mold shown in Fig. 2 was used to make the attachments. An angle of 30 deg was manufactured for the bent portion of the attachment (see Fig. 1). The angle of the attachment is the angle made by the inclined portion of the attachment against the adherend. The attachment has a curvature at the bent portion. In the finite element modeling, the shape of the attachment was that measured from the mold. The selected joint dimensions are shown in Fig. 1. The thickness of the adherend is about 2.6 mm with 32 plies of S2/epoxy laminates. The attachment thickness is 0.9 mm.

Fig. 2 Aluminum mold for manufacturing the composite attachment.

Before curing the joints in the autoclave, proper surface preparation of the adherend and attachment need to be done. The importance of surface pretreatment in the adhesive bonding of composite materials has been well established by a number of researchers [21,22]. Surface treatment of composites is done to remove contamination layers.

In the present investigation, basic steps were applied as follows.

1) Peel ply surface: While manufacturing the composite laminate, a peel ply was used which gives a rough surface that is required for bonding. The use of this peel ply avoids the need to perform sanding with 320 grit sandpaper.

2) Methyl ethyl ketone/acetone treatment: The surfaces to be bonded are treated with methyl ethyl ketone (MEK) or acetone solution to remove the greasy substances formed while handling and other contaminants formed on the composite surface during curing.

3) Distilled water treatment: The degreased surfaces were then cleaned with distilled water and the water-break-free test was performed. The water-break-free test is a quality control test to confirm the lack of surface contamination in which sprayed water sheets off the surface if the surface is clean.

4) Drying: The composite adherends and attachments to be bonded were kept in an oven at about 100°C for 1–2 h to remove any moisture present on the surface. Removing moisture is very important as the presence of moisture was observed to cause poor bonding and thereby result in cohesive failure, i.e., failure between the adherend and adhesive.

A single layer of structural film adhesive FM73M was used to bond the joints in the autoclave under the pressure of 280 kPa, producing an average bond-line thickness of around 0.127 mm along the five interfaces. A ready-to-be-tested single-lap joint with attachments is shown in Fig. 3. The structural film adhesive FM73M was used to bond the specimens in the autoclave using the standard cure cycle for FM73M.

V. Experimental Procedure

Tension tests were conducted using a servohydraulic testing machine (20 klb testing machine from MTS Systems Corporation) at room temperature. All the joints were tested at a stroke speed of 0.001 mm/s until failure. Two to four specimens were tested for each type of design. The onset of failure during the experiment was monitored and failure modes were noted for all the specimens.

For aluminum joints, the joints with and without attachment were tested in tension and the failure loads were compared. The single-lap joint failed at an average load of 23.7 kN, whereas the single-lap joint

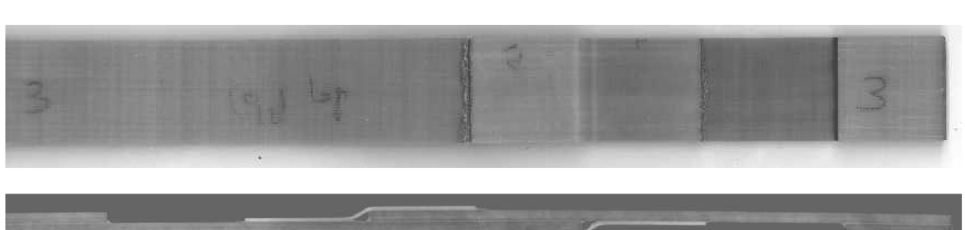
Fig. 3 Composite single-lap joint with attachment.

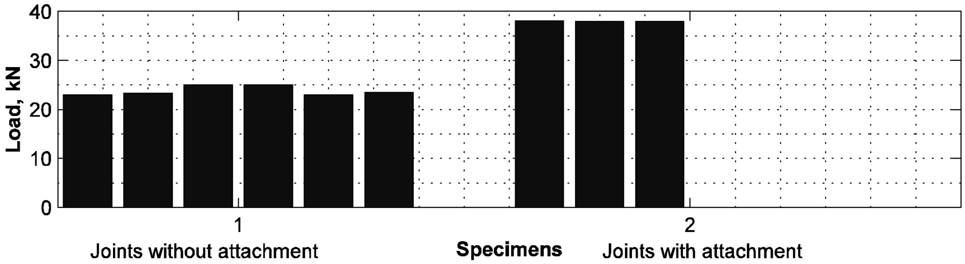

Fig. 4 Ultimate failure loads for the joints with and without attachment.

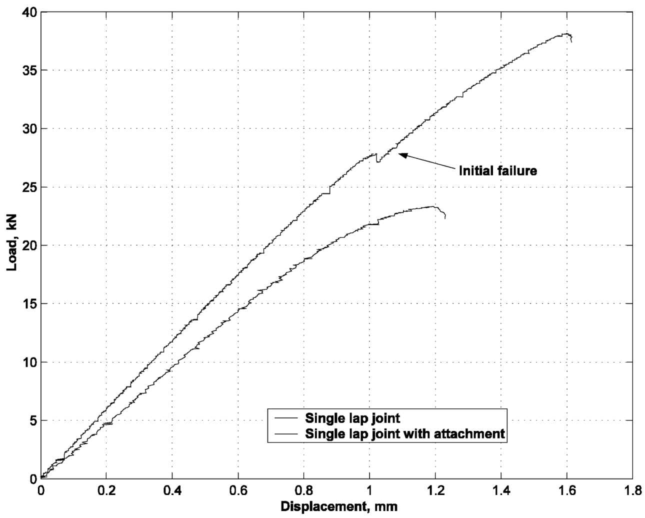

Fig. 5 Load-displacement curve for aluminum joints.

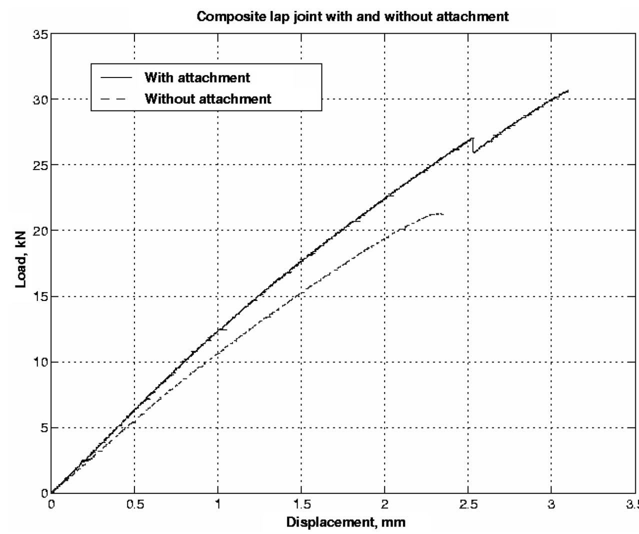

Fig. 6 Load-displacement curves for the composite lap joint with and without attachment.

with attachment failed at an average load of 37.9 kN, thereby giving an increase of 60%. The results of the failure loads are shown in Fig. 4. The load-displacement curve for both types of joints is shown in Fig. 5. For the single-lap joint, the failure started at both edges of the joint, and the joint failed suddenly. For the joint with attachment, the initial failure started in the form of a crack near the corner of the attachment and the sudden decrease in load around 28 kN is attributed to this failure. After the initial failure, the joint took more load before failing suddenly at about 37.9 kN. Using a traveling microscope, it was observed that the final failure occurred when cracks started at the ends of the main interface, thereby causing a sudden catastrophic failure.

For composite joints, it was observed that the conventional single-lap joint specimens failed at an average load of 21.4 kN, whereas the single-lap joints with attachments failed at an average load of 34 kN, thereby giving an increase of 59% in strength. The ultimate loads are listed in Table 1.

The load-displacement curves for both joints are shown in Fig. 6. For the single-lap joint, failure started at both edges of the joint, and the joint failed suddenly. For the joint with attachments, the initial failure started in the form of a disbond crack at the critical interface (see Fig. 1) near the bend of the attachment. The average length of this initial crack formed before the joint failure was 11 mm, with no significant growth beyond the initial crack length. The initial failure started at around 26.5–28 kN, which can be noted as a small load drop in Fig. 6. After the initial failure, the joint took more loads before

Table 1 Ultimate loads of composite single-lap joints with and without attachments

Joint type	Ultimate loads, kN	Average load
Single-lap joint	21.4, 21.6, 20.9, 21.4	21.4
Single-lap with attachments	34.5, 33.4	34
Increase in strength	——	59%

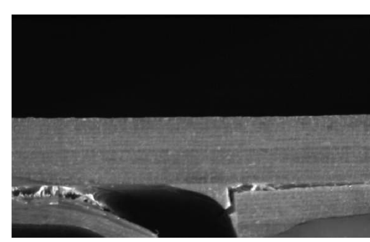

Fig. 7 Failure mode of the composite lap joint with attachment.

failing at about 34 kN. Using a traveling microscope, it was observed that the final failure was the failure of the main interface. The failure mode just before the final catastrophic failure is shown in Fig. 7. The crack at the leading edge of the main interface (see Fig. 1) can be clearly seen.

VI. Finite Element Analysis

Finite element analysis was conducted to observe the critical stress distributions along the different interfaces. For aluminum joints, two-dimensional finite element (FE) analysis using four node plane strain elements was conducted. The addition of the attachment helped in making the singular stresses σ_{yy} compressive along the main interface, as shown in Fig. 8. It can be seen that the magnitude of the shear stresses σ_{xy} is also reduced with the addition of the attachment. Thus, the initial failure of the single-lap joint can be avoided along the main interface. As can be expected, the failure now may potentially occur along the interface of the attachment and the adherend.

The stress distributions along the main interface for the single-lap joint and along the interface of the attachment and adherend for the joint with attachment are shown in Fig. 9. From the figure, we can see that the peak peel stresses along the attachment interface are small

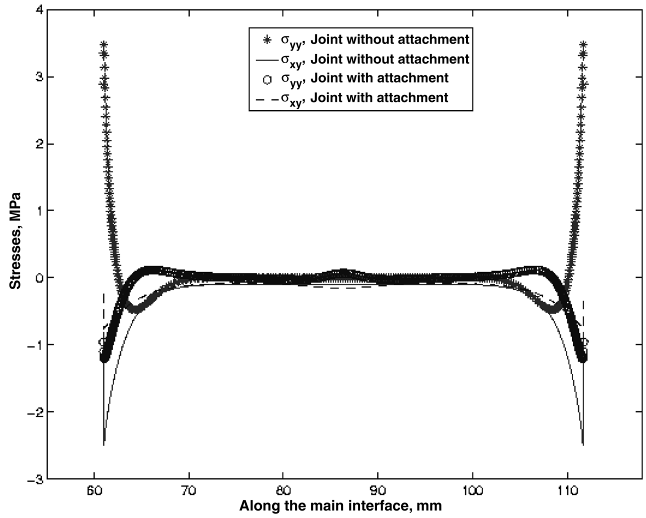

Fig. 8 Stress distribution for aluminum single-lap joints with and without the attachment.

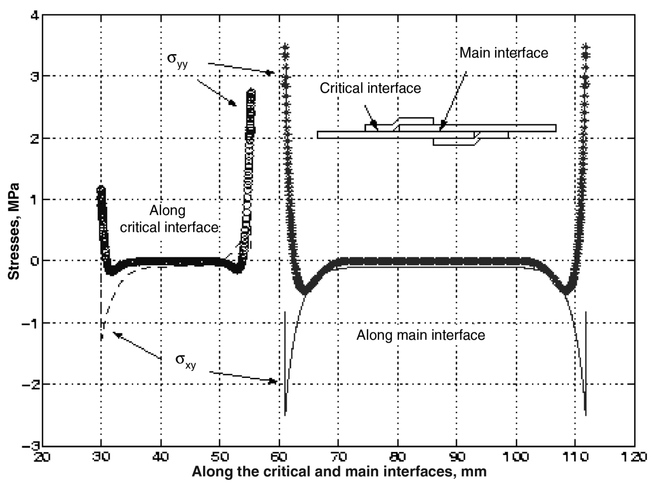

Fig. 9 Stress distributions along the critical interface, and main interface.

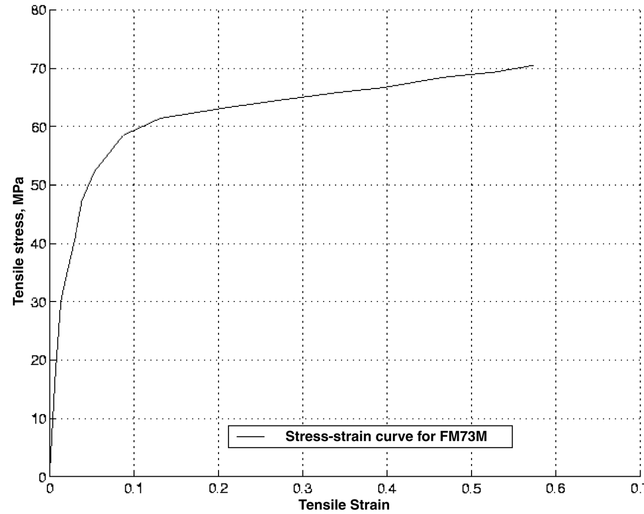

Fig. 10 Tensile stress-strain curve for FM73M.

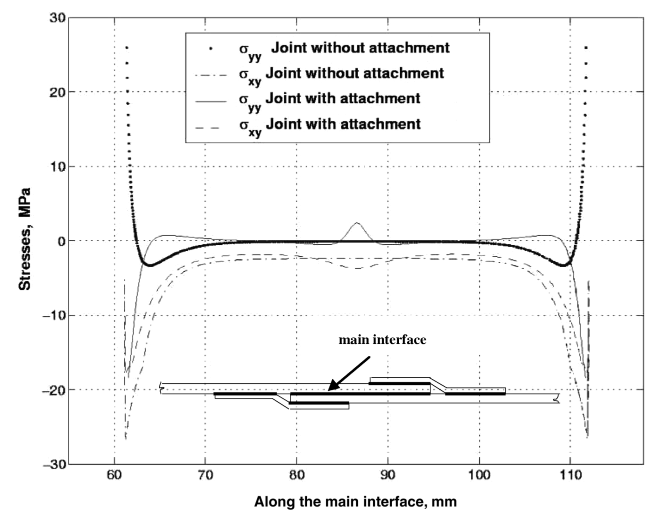

Fig. 11 Comparison of interfacial stress distributions along the main interfaces for single-lap joints with and without attachments.

compared with the peak σ_{yy} stresses along the main interface for the joint without attachment. This may cause the failure of the attachment interface at a higher load than the failure load for the main interface of the single-lap joint.

From the preceding discussion, it can be seen that these factors contribute to the improved performance of the single-lap joint with attachment. Now the critical interface is that of the attachment and adherend with high-tensile peel stresses developed along it.

Finite element analyses with two-dimensional plane strain quadrilateral elements were performed for composite single-lap joints with and without attachments to compare the interfacial stress distributions. Very fine meshes were used near the places where stress singularities exist. In the adhesive layer, eight elements across the thickness were used. The elastic constants of FM73M film adhesive and S2 glass/epoxy composite are shown in Table 2. For simplicity, the adherend and attachment laminates were represented by homogeneous solids whose effective elastic moduli were calculated following Sun and Li [23]. Because the FM73M film adhesive is highly nonlinear, as shown in Fig. 10, it was modeled as an elastic–plastic material obeying the von Mises yield criterion and the associated flow rule. The curve in Fig. 10 was derived from the shear stress–strain curve obtained by the manufacturer using a lap shear test of the adhesive.

Table 2 Material properties of S2/8552 and FM73M

Material	Properties
FM73M	$E = 2.3$ GPa, $\nu = 0.31$
S2 glass/epoxy	$E_1 = 50$ GPa, $E_2 = 20$ GPa, $E_3 = 20$ GPa; $\nu_{12} = 0.27$, $\nu_{23} = 0.4$, $\nu_{13} = 0.27$; $G_{12} = 7$ GPa, $G_{23} = 3.5$ GPa, $G_{13} = 7$ GPa

The normal and shear stresses σ_{yy} and σ_{xy} along the main interface at the midplane of the adhesive under an applied tensile load of 21.4 kN for both single-lap joints with/without attachments are shown in Fig. 11. As in the case of aluminum joints, it can be seen that the addition of attachments has the effect of making the normal stress compressive and reducing the shear stress. The stress distributions along the critical interface, i.e., the interface of the attachment and the adherend, are presented in Fig. 12 along with the stress distributions along the main interface in the conventional single-lap joint.

As seen from the experimental results, the addition of attachments shifts the failure location from the main interface to the interface (denoted as critical interface in Fig. 1) between the attachment and adherend. Along this critical interface, the initial failure in all the specimens occurred at the bend region of the attachment. As can be seen from the stress distributions in Fig. 12, the end of this interface region is most critical and hence the initial failure is expected to initiate from this region. The initial failure forms a crack of a maximum length around 11 mm along the critical interface before the joint suffered the final failure.

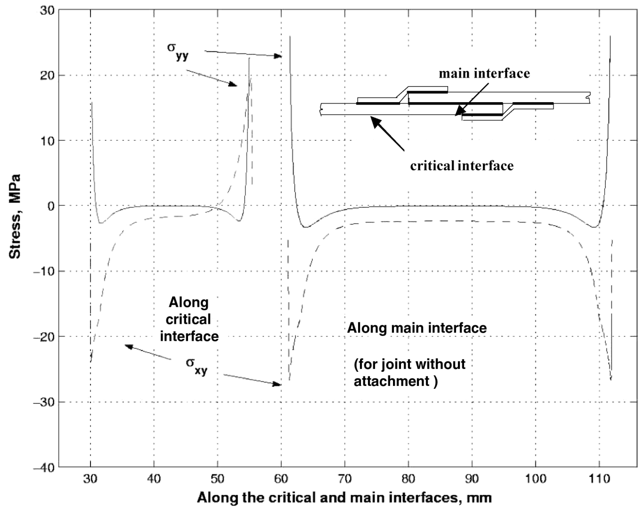

Fig. 12 Comparison of stress distributions along the critical and main interfaces of single-lap joints with and without attachments.

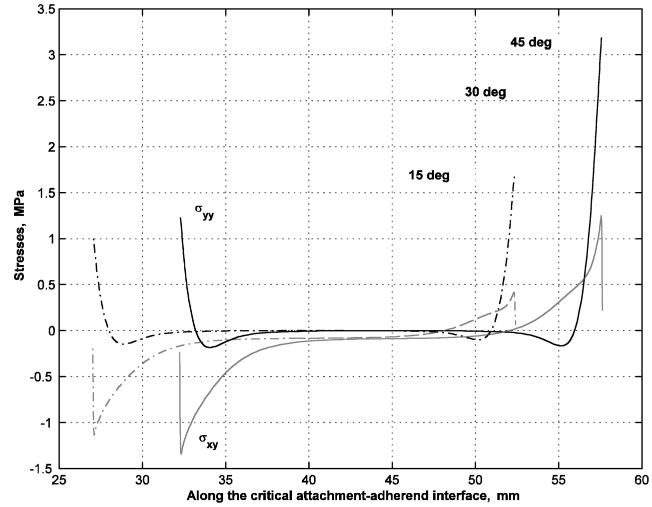

Fig. 14 Effect of the angle of attachment on the critical interface stress distribution.

VII. Parametric Study

The attachment plays an important role in transferring the load by providing an additional path of load transfer. The geometrical parameters of the attachment like the angle, thickness, and length play an important role in deciding the optimum geometry for the load transfer. With a view to studying the effect of these parameters on the ultimate strength of the joint, a numerical and experimental parametric study was conducted. This also helps to establish design guidelines for further research on this joint. Because the factors affecting aluminum and composite single-lap joints are somewhat different, separate parametric studies were conducted for each type of the joint.

A. Aluminum Joints

1. Angle of the Attachment

The details about the angle of attachment are shown in Fig. 13. The angle of attachment is the angle made by the inclined portion of the attachment with the horizontal. The attachment used in the experiments has a curvature at the bent portion. To determine the angle of that curvature, measurements of the actual angle were taken from the attachments. It has been observed that the angle of the curvature is nearly the same as the angle of the attachment θ with a variation of ± 5 deg for the different angle attachments. Based on these measurements of the angles from the attachment, the angle used for the curved portion of the attachment is taken the same as the attachment angle as shown in Fig. 13. The radius of curvature is taken as the thickness of the attachment. The joints tested so far used an angle of 30 deg. Finite element analysis was conducted to find out the effect of this angle on the stress distribution along the critical interface. An adhesive line of thickness 0.127 mm, averaged from the test specimens, is used in the model to account for the FM73 adhesive bond line. The interface stresses are those along the midline of the adhesive layer. The results are shown in Fig. 14 for the joints with a constant attachment thickness of 0.75 mm. It can be seen from the plot that as the angle of attachment is increased, there is an increase in the peak stresses near the right critical point. The plots are spaced so that the stress distributions can clearly be seen. A zoom-in of the same plot in Fig. 15 clearly shows that decreasing the angle is

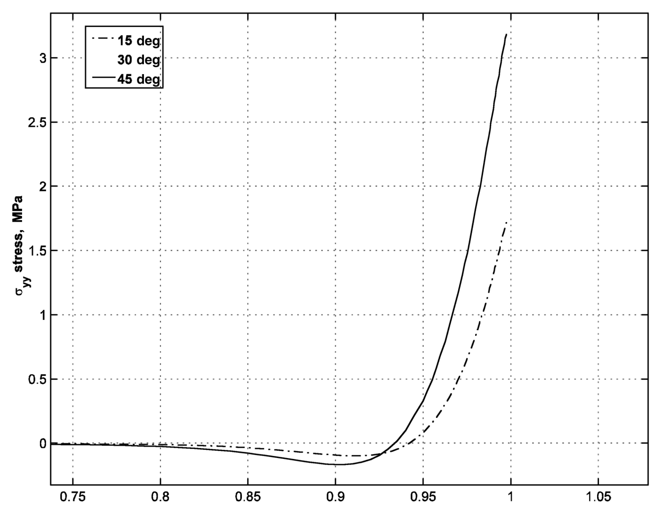

Fig. 15 Effect of the angle of attachment—right hand side view of the critical interface.

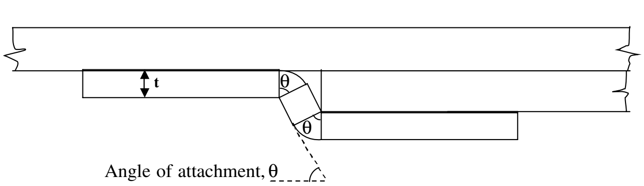

Fig. 13 Geometric details of the attachment region.

beneficial for the strength of the joints. This is experimentally verified by testing the joints with attachments of angles −15, 30, 45, and 60 deg. The average ultimate load for the joint with 15 deg attachment is 40.3 kN, with 30 deg attachment is 37.9 kN, with 45 deg attachment is 35.9 kN, and with 60 deg attachment is 31.4 kN. The results are shown in Fig. 16. The failure modes of all the joints are the same. Referring to Fig. 17, the effect of the angle can be explained by the fact that as the angle of attachment increases, the vertical component of the force P along the attachment $P \sin\theta$ increases with θ. This increases the normal stress distribution along the critical interface, as shown. It can be said that the attachment with the 15 deg angle will perform better and can thus be taken as an optimum angle for the purpose of further studies. Reducing the angle further might help, but may not be practicable.

2. Thickness of the Attachment

Thickness of the attachment plays a crucial role in the design of the joint. In all the preceding tests, a thickness of 0.75 mm was used for the aluminum attachments and 3 mm for the adherends. To see the effect of increasing thickness, a parametric study increasing the thickness for a given angle of attachment θ was conducted. The thickness of the attachment t was changed from 0.75 to 3 mm, in steps of 0.75 mm. Thus, the ratio of the thickness of attachment to the adherend was changed from 1:4 to 1:1. The stress distributions along

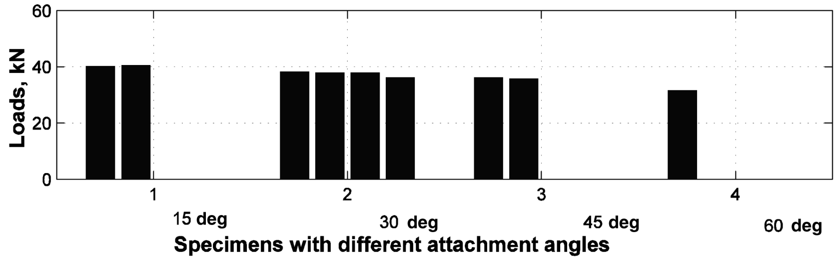

Fig. 16 Ultimate failure loads for joints with different angle attachments.

Fig. 17 Free body diagram of the attachment and adherend.

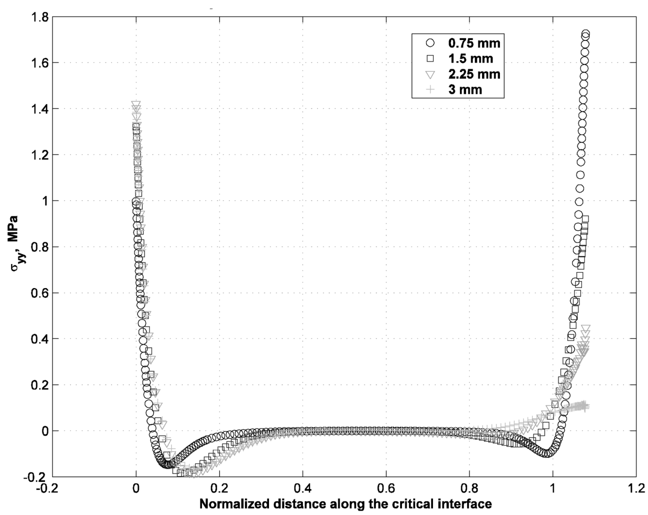

Fig. 18 Effect of the attachment thickness on the interface stresses (15 deg attachment).

the critical interface for the joints with 15 deg attachment with varying thicknesses are shown in Fig. 18. The stress distributions for joints with 30 and 45 deg attachments are shown in Figs. 19 and 20, respectively. It can be seen that increasing the thickness decreases the

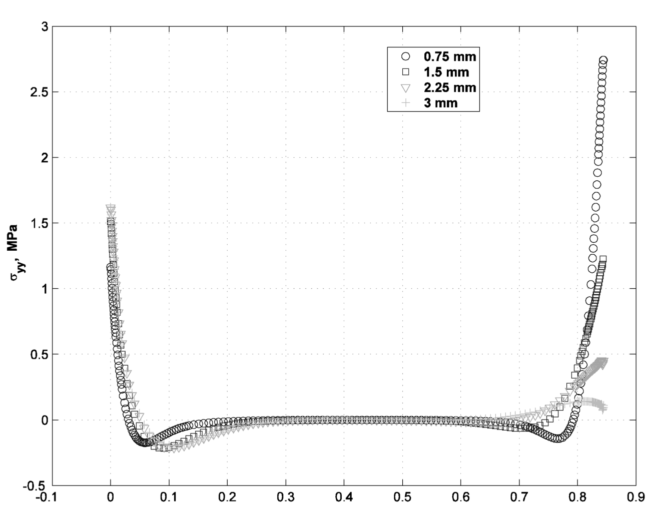

Fig. 19 Effect of attachment thickness on the interface stresses (30 deg attachment).

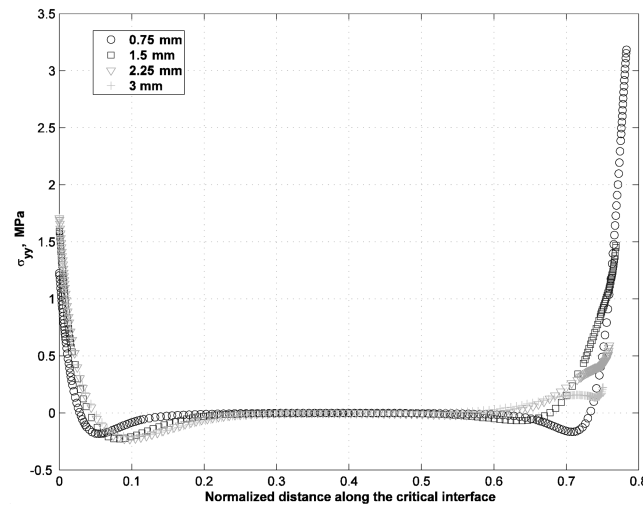

Fig. 20 Effect of attachment thickness on the interface stresses (45 deg attachment).

normal (peel) stress distribution along the critical interface. As the thickness of the attachment equals the adherend thickness, the singular stresses near the curved portion of the attachment are reduced so much that the failure may not initiate from that location. It might potentially initiate from the left edge of the interface, where the singular stresses are high.

As shown in Fig. 21, we can see that as the thickness is doubled, the joint did not fail, but yielded. A small crack initiation can be seen from the left edge of the critical interface, which did not propagate further. For the joint with thick attachment, the ratio of thicknesses of attachment and adherend is 1:2 and for the joint with thin attachment, the ratio is 1:4. Larger thickness of the attachment helps in transferring more load through the attachment area and thus in reducing the interfacial stress distribution between attachment and the adherend as seen. It can be concluded that as the thickness ratio increases, the interfacial stresses are not high enough to induce any failure along the critical interface. Hence, the joint strength increases. The interesting observation is that local yielding of the adherend occurs and the joint never fails.

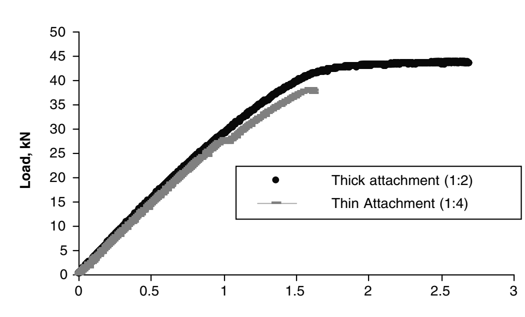

Fig. 21 Load-displacement curve for different thickness attachment joints.

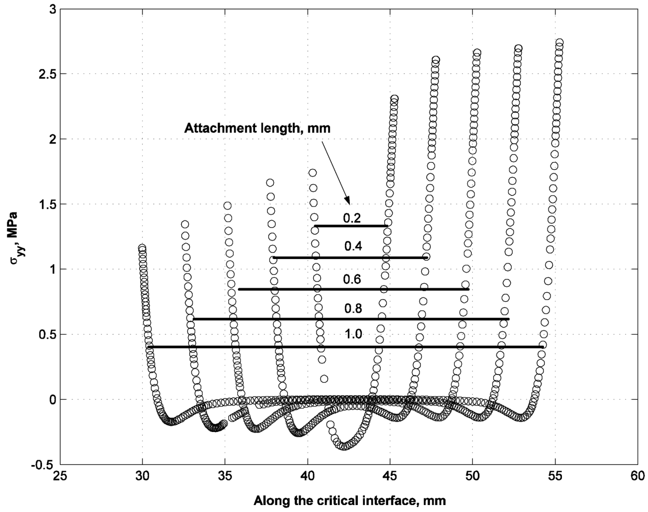

Fig. 22 Effect of the length of attachment on the stresses along critical interface.

It can also be seen from Figs. 18–20 that as the angle of attachment increases, the stresses at the right side of the critical interface increase for joints with the same attachment thickness. The same trend was discussed in the preceding section on the angle of attachment.

3. Length of the Attachment

Just as increasing the length of the lapped region does not improve the joint strength significantly because of the fact that the load transfer takes place mainly along the ends, increasing the length of the attachment does not have a significant effect on the ultimate strength of the joints with attachment. We can see the trend from Fig. 22. Stress distributions along the critical interface for the joints with attachment lengths of 5.08, 10.16, 15.24, 20.32, and 25.4 mm were shown. No experimental testing was conducted for verification. In all the experimental testing, a length of 25.4 mm was used for attachment for both legs.

Hence, in the case of aluminum joints, the angle of attachment, the thickness, and the length play a significant role in determining the strength of the single-lap joint. For composite joints, owing to the layered nature of the adherends and attachments, we will see that some more variables come into play. Even as the effect of the angle of attachment and length is still valid for the composite joints as well, we will see that the thickness is replaced by stiffness of the attachment. A new variable, the ply orientation also comes into play as seen in the following section.

B. Composite Joints

1. Effect of the Ply Orientation next to the Adhesive Layer

In the preceding experiments, the stacking sequence used for the adherends was $[0/90/0/90]_{4s}$ and for the attachments was $[0]_{12}$. Here, the ply next to the adhesive layer was a 0 deg ply. Because this ply may have an effect on the failure modes of the joints, the effect of changing this ply to a 90 deg ply was investigated.

From the results listed in Table 3, we can observe that placing a 90 deg ply next to the adhesive layer is not beneficial to the joint strength. The failure load of the single-lap joint without attachments was 16.8 kN, which is 21% less than the load of 21.4 kN for the $[0/90/0/90]_{4s}$ adherends. For the single-lap joint with attachments, the average failure load dropped by 27% with the use of $[90/0/90/0]_{4s}$ adherends. The reason for the reduction in joint strength with the $[90/0/90/0]_{4s}$ adherends is that failure occurs in the 90 deg ply in the adherend as opposed to the cohesive failure of the joints with the $[0/90/0/90]_{4s}$ adherend. A typical failure surface in a single-lap joint with $[90/0/90/0]_{4s}$ adherends is shown in Fig. 23 in which the transverse matrix cracks in the 90 deg ply are visible.

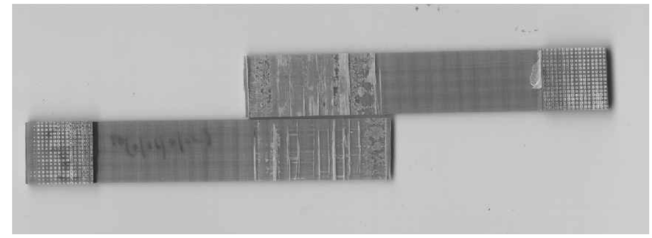

Fig. 23 Failure mode of the joint with $[90/0/90/0]_{4s}$ adherends.

In view of the foregoing, it can be concluded that a 90 deg ply in the adherend next to the adhesive layer can alter the failure mode and lower the joint strength, and hence is not recommended. Nevertheless, it still demonstrates that the design concept of attachment works equally well for the adherends having 90 deg plies on the surface.

Table 3 Effect of 90 deg ply next to the adhesive layer

Joint type	Average ultimate load, kN for $[0/90/0/90]_{4s}$	Average ultimate load, kN for $[90/0/90/0]_{4s}$
Single-lap joint	21.4	16.8
Single-lap with attachment	34	24.7
% difference	59	47

2. Effect of Attachment Stiffness

A composite joint offers more parameters for an efficient joint design like studying the effect of stiffness of the attachment by changing the number of 0 deg plies in the attachment, which are the primary load carrying members of the composite. Hence, a parametric study to investigate the effect of the stiffness of the attachment by changing the number of 0 deg layers instead of changing the thickness of the attachment was conducted.

Two attachments, a stiffer $[0]_{12}$ laminate and a softer $[0/90/0]_{2s}$ laminate, were used for the joints with adherends made of $[0/90/0/90]_{4s}$ laminate. The ultimate failure loads for both types of joints are presented in Table 4. A total of four joints were tested for each type. It appears that there is no significant difference in the failure loads. It was observed that the failure modes of the joints were also the same, with the failure initiating from the critical interface near the bend region for both types of joints. The final failure occurred catastrophically in the form of cracking in the main interface following the initial failure.

VIII. Conclusions

From this investigation, it was concluded that the addition of thin attachments on both sides of the lapped region in a single-lap joint helps redistribute the load transfer from one adherend to the other and, as a result, can alter the characteristics of the interfacial stress distribution along the bond line. The addition of attachments makes the peel stresses compressive, changes the failure mode, and contributes to the higher ultimate load of the joint when compared with the single-lap joint. The failure modes of the single-lap joint with attachment are as follows: initial crack initiation at the interface of the fillet portion of the attachment and adherend and secondary failure along the main interface, followed immediately by final catastrophic failure. Through the parametric study, it was found that, in general, increasing the angle of attachment decreases the failure load and, beyond a certain point, the length of the attachment does not have significant effect on the ultimate strength. In the case of

Table 4 Effect of the stiffness of attachment

Specimen type	$[0]_{12}$ attachment	$[0/90_2/0/90_2]_s$ attachment
Ultimate loads, kN	33.4, 34.5	35.9, 34
Average	34	34.9

composite joints, failure modes of the new joint with attachments, as well as the conventional single-lap joint, are affected by the ply next to the adhesive layer. Placing a 0 deg ply in the adherend next to the adhesive layer is beneficial to the joint strength, whereas a 90 deg ply would crack before the adhesive fails. For the configuration of the attachment considered in this study, it can be concluded that the critical location for initial failure in the new joint design is at the end of the interface between the adherend and the attachment near the bend of the attachment. Increasing the stiffness of the attachment by increasing the number of 0 deg plies, without changing the thickness, does not seem to be able to alleviate the interfacial stress at this critical location and thus does not have noticeable effects on the joint strength.

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