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# Adding Additional Load Paths in a Bonded/Bolted Hybrid Joint

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**Hybrid (bonded/bolted) joints are usually used in lap joints in order to achieve the fail-safe capability. However, the mechanical bolt is inactive until the adhesive bond fails, making the hybrid joint weightwise inefficient. In the present work, a new design of a hybrid joint with attachments was conceived and investigated. This design used thin-plate attachments to provide an additional load transfer path to activate the load-bearing capability of the bolt. Experimental investigations were conducted on the conventional joint designs and the new joint design. The joint strength of the new design was found to be 80% higher than the conventional hybrid joint. In addition to the development and testing of the new joint design, finite element analysis was performed to study the load distribution in different parts of the joint and to compare stress distributions in different joint configurations.**

## I. Introduction

ADHESIVE bonding and mechanical fastening are the two major techniques for jointing structures. Each method has its advantages and disadvantages. For composite structures, the adhesive bonding technique seems to be more attractive than mechanical fastening as this process does not require drilling holes (and thus cutting off fibers) through the composite structure. Moreover, reduction in weight can be obtained by using bonded joints instead of joints using mechanical fasteners. However, due to the difficulty in controlling the quality of adhesive joints, there is great uncertainty in the load-bearing strength and durability of adhesive joints. For instance, it has been found that the strength of a bonded joint is very sensitive to the bondline thickness [1] and achieving a particular adhesive thickness during assembly of structures is difficult. For this reason, it is a common practice to add mechanical fasteners on top of adhesively bonded joints to provide the desired fail-safe assurance. This is the main reason for using hybrid joints.

A number of researchers [2–8] have conducted experimental and analytical studies on hybrid joints. An analytical investigation was conducted by Hart-Smith [2] on a hybrid joint with stepped lap joints between titanium and carbon fiber reinforced plastic. It was found that hybrid joints do not achieve any significant advantage over adhesive bonding. In addition to the experimental observations, several researchers [4–8] proposed various numerical approaches or analytical solutions to analyze hybrid joints. Chan and Vedhagiri [4] conducted experiments with composite joints as well as a parametric study using finite element analysis to investigate the stacking sequence effect on joint strength. In that work, it was found that bolts do not take an active role in load transfer before the initiation of failure in the bonded part of the joint, a phenomenon also observed by Hart-Smith [2] and Kweon et al. [6], who considered a double lap hybrid joint with composite and aluminum adherends. Barut and Madenci [8] developed a semi-analytical solution method for stress analysis of a hybrid joint and found that most of the load is transferred through the adhesive, even though it has a lower modulus as compared to the bolt. In all existing designs of hybrid joints, bolts do not participate in taking loads until the complete failure of the bondline. In other words, bolts stay idle until failure in the adhesive part of the joint occurs. It is evident that the main issue of improving the hybrid joint is to come up with a design that would involve bolts in contributing to the load bearing at the joint before failure of the adhesive.

Another approach in improving bonded joints was pursued by Qian and Sun [9], who proposed an idea of using separate attachments to provide additional load transfer paths at the joint. In this proposed design, in addition to additional load transfer paths, the localized interfacial stress concentrations near the joint edge are reduced. With the attachments used in double strap joints, the joint strength increment was found to be 20–30% compared to the conventional double strap joint. A similar approach was employed by Turaga and Sun [10] to improve single-lap bonded joints. Experiments were conducted with aluminum as well as composite adherends. Failure loads for the conventional single-lap joints and single-lap joints with attachments were compared. The strength of the joint with angular attachments was found to be 59% higher than that of the conventional joint. These two approaches [9,10] discussed above indicate that the joint strength of bonded joints can be enhanced significantly by using attachments to create additional load transfer paths at the joint.

The present study proposes a new hybrid (bonded/bolted) joint design, which can achieve a substantially higher joint strength compared to the existing hybrid joint design. This new hybrid joint design uses a concept similar to that proposed by Turaga and Sun [10] for bonded single-lap joints. The proposed new hybrid joint design is able to activate bolts to load bearing before the adhesive fails, a capability that cannot be achieved by conventional hybrid joints.

## II. Experimental Details

Three types of conventional joint configurations and one new hybrid joint were considered for experimental comparisons. The joint configurations were the conventional single-lap bonded joint, bolted joint, conventional hybrid (bonded/bolted) joint, and the new hybrid joint, named the hybrid joint with attachments. A sketch view of the proposed new hybrid joint design is shown in Fig. 1. The width of the specimen was 38.1 mm and the bolt diameter was 6.35 mm. Adherend and attachment thicknesses were 3.18 and 1.59 mm, respectively. The bend angle $\theta$ of the attachment was 14° (Fig. 1).

All the conventional joint specimens are different special cases of the proposed new hybrid joint design. For example, if attachments are removed, the new hybrid joint design becomes a conventional hybrid joint. Similarly, without attachments and the bolt, the joint becomes a typical bonded joint. Therefore, sketch views of other joint configurations are not shown.

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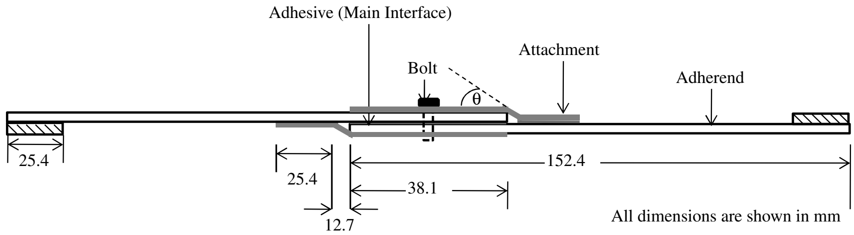


**Fig. 1 Sketch view of the new hybrid joint with attachments.**

### A. Materials

Al-alloy 2024-T3 were used for all adherends. Dimensions of adherends were maintained same in all joint configurations. For the attachment part in the new hybrid joint design, Al-alloy 6061-T6 was used. A two-phase structural paste adhesive Hysol EA9394 (Henkel Company) was used for bonding. Compsi-Lok fasteners (Monogram Aerospace Fasteners) were used for the mechanical fastening. Al-alloy 2024-T3 tabs were used for all specimens.

### B. Specimen Preparation

Al-alloy 2024-T3 sheets were cut into the required dimensions of the adherends using a water-jet cutting machine. Aluminum alloy adherends need a good quality surface treatment for strong bond. The surfaces of adherends were polished using aluminum oxide sandpaper of grit size 100. Pasa jell 105 (Semco Company) was applied on the surfaces of the adherends and then cleaned with cold water after 20 min and dried. Hysol EA9394 adhesive was prepared by mixing two-phase materials provided by Henkel Company. To avoid the global eccentricity effect, aluminum end tabs of the same thickness as the adherend were bonded at both ends of the specimen. Teflon sheet (Dupont) spacers were used to obtain the desired bondline thickness. These spacers were placed in the area between the main joint and the end tabs. On the top of the spacers, aluminum sheet of the same thickness as adherends were placed. Whole setup was pressed with weight to get a uniform bondline thickness. Bondline thicknesses in all specimens, except bolted joints, were controlled by placing spacers. This was the procedure used for the bonded joint.

For the hybrid joint, a hole was drilled at the center of the overlapped region and a single bolt was fastened. For the new hybrid joint with attachments, an attachment was put on the top of the adherend before drilling the hole and fastening the bolt. One end of the attachment (the end on the top of the overlapped region) was not bonded to the adherend and only the bolt keeps it together with the adherend, as shown in Fig. 1. The other side of the attachment was bonded to the adherend using the same adhesive material. All joint specimens were prepared carefully to maintain the invariability of the manufacturing process. The images of all joint specimens, with labels, are shown in Fig. 2.

## III. Experimental Results

Quasi-static tension tests were conducted at room temperature on an MTS machine with load capacity of 100 kN. A crosshead displacement rate of 0.01 mm/s was used to test all joint specimens. Three to four specimens were tested for each joint configuration. Individual load-displacement curves of all joint configurations and their failure behaviors are discussed in the following sections.

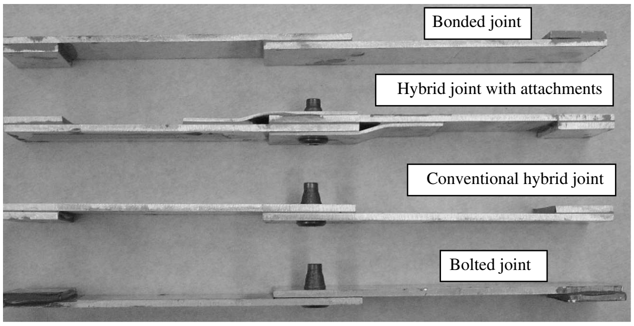


**Fig. 2 Joint specimens before testing.**

### A. Bonded Joint

For the bonded joints, the load-displacement curves for three specimens are given in Fig. 3. The failure was catastrophic and the average failure load (joint strength) of the bonded joints was found to be 26.2 kN. It is noted that there is some variation in the failure loads among the three specimens. This may be due to the small variation (±5%) in the bondline thickness of these joints, which is difficult to control precisely.

### B. Bolted Joint

The load-displacement curves (Fig. 4) of the bolted joints were nonlinear because of the bearing failure mode for which the damage accumulation is progressive. The average failure load of the bolted joints was found to be 17 kN, which was less than the average failure load of the bonded joints. It should be noted that for these specimens, the failure load was controlled entirely by the bearing strength of the bolt.

### C. Conventional Hybrid Joint

The conventional hybrid joint specimens were also tested under the same test conditions as bolted and bonded joints. There were two stages of failures observed in the conventional hybrid joint, as shown in the load-displacement curves in Fig. 5. Initial failure was a complete debonding failure at the main interface. After complete debonding, the bolt carries the load and follows the load-displacement curve for the bolted joint. The final failure is the bolt failure, as shown in the second segment of the load-displacement curve (Fig. 5). Interestingly, the initial failure (bond failure) load of the conventional hybrid joint was found to be 26.5 kN, which is very close to the failure load of the bonded joint. Also, the final failure (bolt failure) load was found to be 16.4 kN, which is close to the

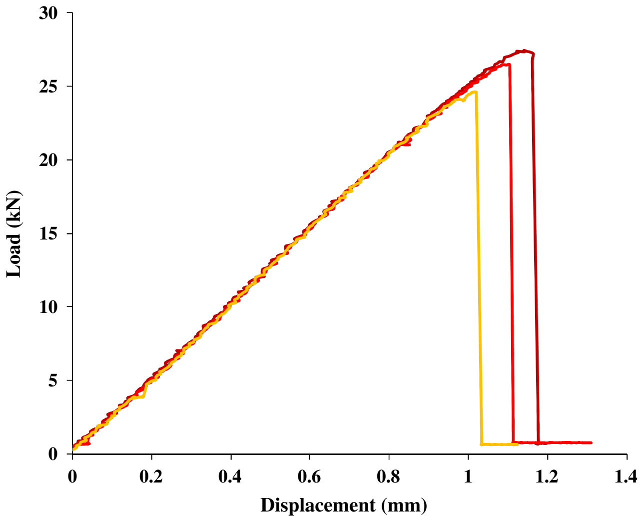


**Fig. 3 Load-displacement curve for the bonded joint.**

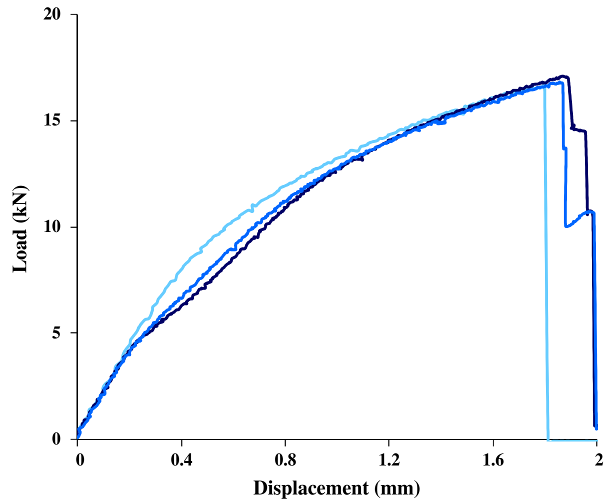


**Fig. 4 Load-displacement curve for the bolted joint.**

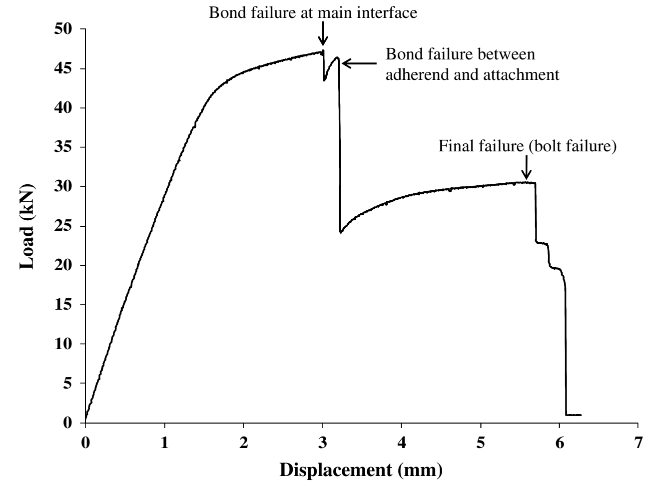


**Fig. 6 Load-displacement curve for the hybrid joint with attachment.**

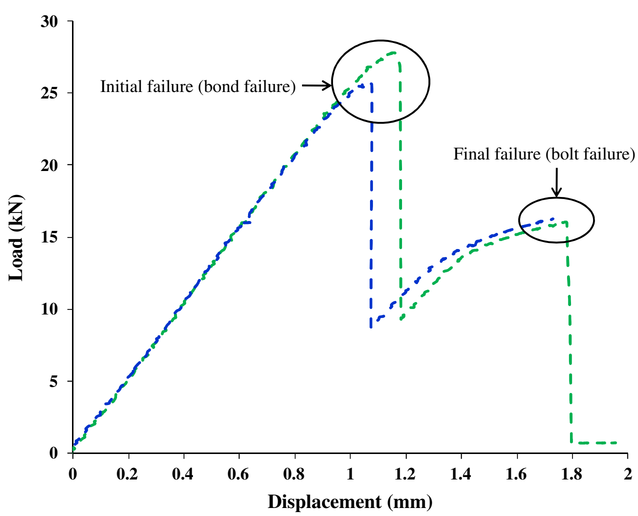


**Fig. 5 Load-displacement curve for the conventional hybrid joint.**

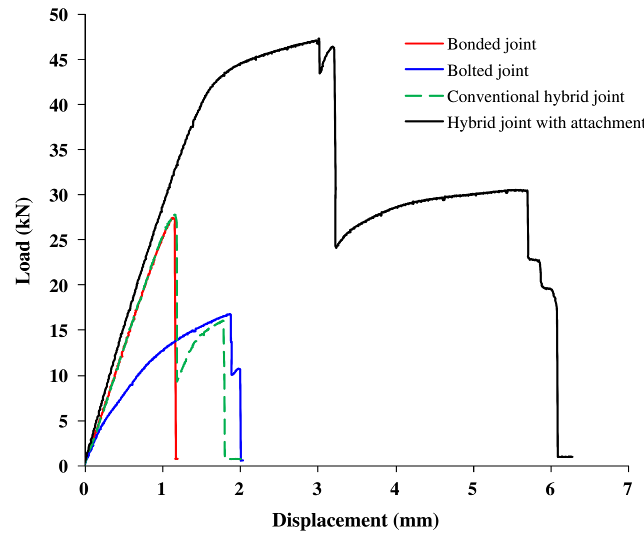


**Fig. 7 Comparison of load-displacement curves for all joint configurations.**

failure load of the bolted joints. It shows that the hybrid joint strength is as good as a bonded joint with a fail-safe load capability provided by the bolt.

### D. New Hybrid Joint Design (Hybrid Joint with Attachments)

The load-displacement curve for the new hybrid joint is shown in Fig. 6. It was observed in the experiment that the first failure (bond failure) occurs at the main interface between the two adherends. The first peak load in the load-displacement curve indicates the complete debonding of the main interface. A detailed description of each segment of the load-displacement curve of the new hybrid joint with attachment is also shown in Fig. 6. After the first failure, debonding occurred between the adherend and one attachment immediately. This second stage of debonding can be seen as the second peak in load-displacement curve. It was observed that only one attachment got detached from the adherend. After failure of one attachment, the bolt carried the load and followed a nonlinear path caused by the bearing failure mode. The third peak in the load-displacement curve shows the final failure (bolt failure). The average failure loads for the initial and final failure were 46.8 and 29.5 kN, respectively.

Figure 7 shows a comparative plot of the load-displacement curves for all joint configurations. It is interesting to note that the bonded joint and the conventional hybrid joint have nearly the same stiffness as well as failure loads. On the other hand, the new hybrid joint with attachments has a significant increase in the initial and final failure loads as compared to the conventional hybrid joint.

## IV. Discussions

Figure 8 shows a comparison of the failure loads of all joint configurations in a bar diagram. It is evident that the scatter is insignificant for all joint specimens tested. The scatter in the bonded joint failure (initial failure) is more than that in the bolt failure (final failure). While the bonded joint failure and the initial failure in the

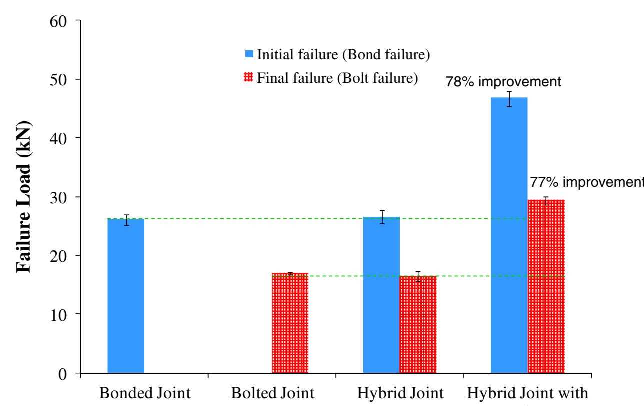


**Fig. 8 Comparison of failure loads for all joint configurations.**

conventional hybrid joint occur at the same load, there is a 78% improvement in the initial failure load of the new hybrid joint with attachments. The second segment of the load-displacement curve for the conventional hybrid joint and the hybrid joint with attachments can be compared with the bolted joint. It can be seen that final failure of the conventional hybrid joint occurs at the same failure load as the bolted joint. However, the new hybrid joint with attachments yielded an improvement of 77% in the joint strength over that of the bolted joint. A simple explanation for this significant increase in the final failure load is that in the new hybrid joint design, one attachment failed by debonding from the adherend but the other attachment continues to provide extra stiffness to the joint thereby increasing the final failure load. It is remarkable that hybrid joint with attachments enhanced the joint strength in both stages of failure by 78% when compared with the conventional hybrid joint.

Another perspective to look at this efficient and novel technique is to check the specific strength, as it is an important structural design variable. Therefore, a basic comparison of the specific strength of the hybrid joint with attachment and the conventional hybrid joint was calculated, as shown in Fig. 9. The specific strength of the new hybrid joint with attachments is normalized with respect to the conventional hybrid joint. It can be seen in Fig. 9, that there is approximately 60% increase in the specific strength of the hybrid joint with attachments for both stages of failure. The specific strength calculation shows that even though adding attachments to the hybrid joint increases the overall weight of the joint, it yields a significant increase in specific strength.

## V. Finite Element Analysis

In the new hybrid joint design, the attachment provides an additional load transfer path from the adherend to the bolt, thus reducing the load carried by the main interface between the adherends. To calculate the percentage of the applied load transferred through the attachment, a three-dimensional finite element analysis was performed using the commercial finite element code ABAQUS 6.8-1 [11]. The eight-noded brick elements (C3-D8) were used to model the whole joint. Frictionless contact was defined between the attachment and the adherend at the overlapped region. Adhesive was modeled at all the bonded regions. Contact elements were used to model the contact between the bolt and adherends. For the calculation of the load distribution between the attachment and adherend, a relatively coarse finite element mesh was used. On the other hand, for the calculation of interfacial stress distribution between adherends, very fine meshes are needed and, thus, an equivalent 2-D model was used. The details of the 2-D model are given in the subsection below.

Material properties used for the analysis are listed in Table 1. All materials were assumed to be linearly elastic. A uniform load was

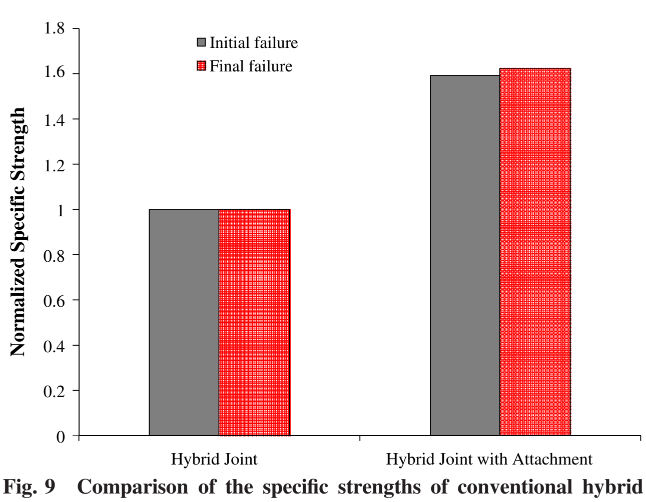


**Fig. 9 Comparison of the specific strengths of conventional hybrid joint with hybrid joint with attachments.**

**Table 1 Material properties**

| | Aluminum (adherends) | Hysol (adhesive) | Titanium (bolt) |
|---|---|---|---|
| Modulus, GPa | 71 | 4.3 | 112 |
| Poisson's ratio | 0.33 | 0.35 | 0.33 |

applied at the ends of the joint. The 3-D finite element (FE) model of the hybrid joint with attachments is shown in Fig. 10.

### A. Load Transfer Analysis

From the 3-D finite element analysis, loads carried by the adherend and attachment of the new hybrid joint are obtained and shown in Fig. 11. The loads transferred through the angular attachment and the adherends were found to be 21 and 79%, respectively, of the applied load. This result indicates that 21% of the load is transferred from one adherend to the other via the attachment and the bolt. In other words, only 79% of the load passes through the original bonded interface giving rise lower interfacial stresses along the bondline.

### B. Peel Stress Analysis

Distributions of interfacial peel and shear stresses between adherends were analyzed for the conventional hybrid joint and the new hybrid joint with attachments. To use very fine finite element meshes to calculate the interfacial stresses which exhibit high stress gradients, an equivalent finite element model was used. In this 2-D model, the cylindrical bolt was modeled as a thick plate with a cross section equal to that of the joint, as shown in Fig. 12. The thickness of the plate bolt was determined by requiring that it has the same volume as the actual cylindrical bolt. The equivalent bolt was placed at the center of the main joint, as shown in Fig. 12 for both cases. The plate bolt was tied to the adherend along the contact surface with the adherend and attachment. A smooth surface-to-surface contact was defined between the adherend and the attachment instead of tying them. For the present purpose, thickness of the adhesive was neglected. The load distribution between the adherend and attachment based on the 2-D model was found to be 77.2% vs 22.8%. This agrees well with that according to the 3-D model.

**Fig. 10 FE model of the hybrid joint with attachments.**

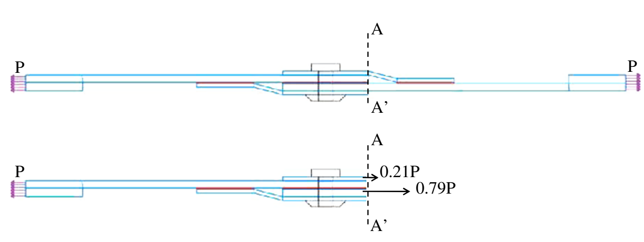


**Fig. 11 Load distribution in adherend and attachment.**

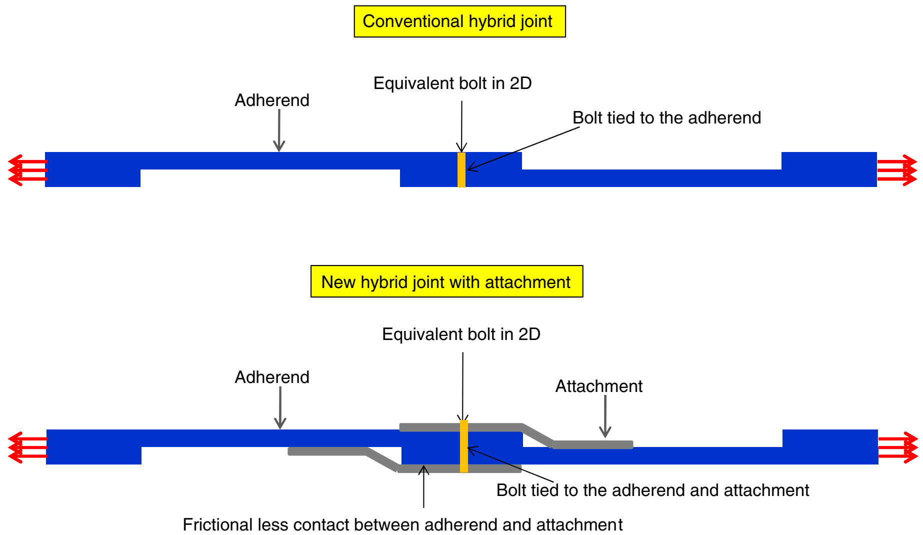


**Fig. 12 Two-dimensional FE model of the conventional hybrid joint and the new hybrid joint.**

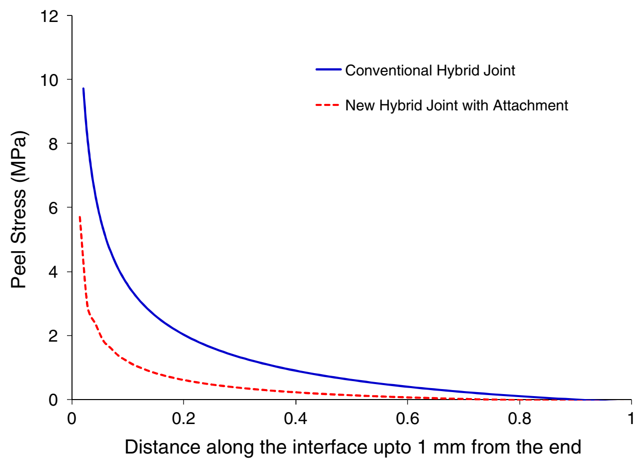


**Fig. 13 Peel stress distribution along the interface.**

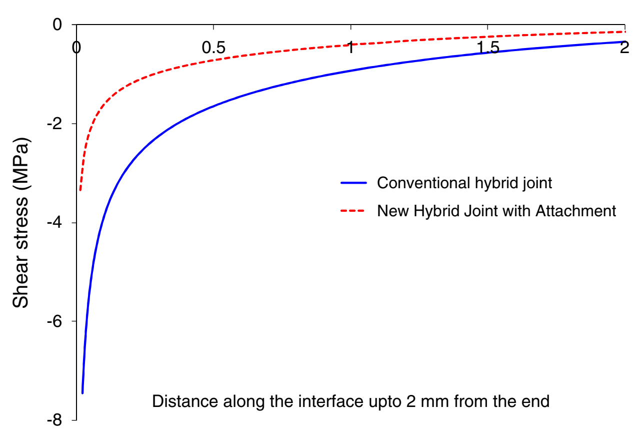


**Fig. 14 Shear stress distribution along the interface.**

The finite element analysis (FEA) results for the peel stress and shear stress distributions along the bonded interfaces of adherends are shown in Figs. 13 and 14, respectively. It clearly shows that the peel stress and shear stress in the hybrid joint with attachments are significantly lower than that of the conventional hybrid joint. This explains why the new hybrid joint achieves a much greater strength. It is conceivable that the joint strength may be further increased by optimizing the thickness and angle of the attachment to reduce interfacial stresses in the hybrid joint with attachments.

## VI. Conclusions

The conventional hybrid joint design was significantly improved by adding an angular attachment. Experiments were conducted for four types of joint configurations: namely, bonded joint, bolted joint, conventional hybrid joint, and the new hybrid joint with attachments. It was found that the initial failure load and the final failure load of the conventional hybrid joint correspond to those of the bonded joint and the bolted joint, respectively. The joint strength of the new hybrid joint with attachments was increased by 78% for the initial failure load (bond failure) and 77% for the final failure load (bolt failure), respectively, as compared to the conventional hybrid joint. The new hybrid joint uses attachments to create additional load paths and, as a result, to reduce the load carried by the bonded interface between the adherends. Unlike the conventional hybrid joint, the bolt starts contributing to load bearing from the beginning of load application. The lower peel stress and shear stress distribution at the interface between the adherends obtained from FEA explains why the new hybrid joint with attachments is able to outperform the conventional hybrid joint.

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