A HYBRID JOINING SCHEME FOR HIGH STRENGTH MULTI-MATERIAL JOINTS

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1 Summary

An advanced method for joining fibre reinforced polymers to metallic substrates has been investigated. The solution was shown to offer improvements in strength, toughness (as indicated by the area under the load-displacement curve) and damage tolerance (residual strength after impact) under a range of test conditions.

2 Introduction

Combining metallic and composite materials in structural applications can lead to greater design freedom, lower cost and lower mass. This is generally accepted within the aerospace, defence and motorsport sectors, and the use of composites continues to grow in mainstream sectors such as the automotive industry. The use of different materials requires the development of appropriate joining technologies.

The notch-sensitivity of composite materials means that mechanical fastening methods often yield reduced strength and excessive weight. Adhesive bonding is sensitive to initial surface preparation, hot/wet environments and may require a large bond area. Furthermore, adhesively bonded joints may exhibit sudden catastrophic failure. These factors tend to lead to a conservative design approach. Previous work suggests that combining bonding with mechanical interlocking can lead to improvements in stiffness, strength and fatigue life compared to standard joining systems [1].

In this work, an advanced joining technique, combining interlocking metallic surface features with adhesive bonding, is evaluated. The surface features take the form of an array of pins, selectively located for minimal disruption to the fibre architecture. They enhance the strength, toughness and damage tolerance of composite-metal joints.

The work described was conducted over a two year period. Initial experiments were conducted to gain a basic understanding of joint performance; this was followed by a more comprehensive study to explore the behavior of the joints over a range of conditions.

3 Joint Manufacturing Methods

3.1 Additive Layer Method

A proprietary additive layer manufacture (ALM) technique was used to form protruding pin arrays on 3 mm thick stainless steel (316L) substrates (Figure 1). The substrates were then grit-blasted with grade-60 grit, rinsed with water and degreased in acetone. Plies of plain woven E-glass were laid up on top to give a nominal cured laminate thickness of 2.5mm. Pin spacing was designed to locate at gaps in the weave architecture so as to minimise fibre disruption.

A vacuum assisted resin transfer moulding (VARTM) process was used to infuse the fibre on a flat tool-plate, and co-cure against the metallic substrate. For this, a quantity of LY564 (Huntsman) epoxy resin was degassed in a vacuum oven at 60 °C for 30 minutes. This was left to cool to 40 °C before adding 35 % wt. of Aradur 2954 (Huntsman) curing agent. The two-part mix was stirred and placed under vacuum at 30 °C for a further 20 minutes before infusing. A heat mat was used to cure the resin. To do this, the temperature was maintained at approximately 60 °C for 2 hours, while consolidation pressure was provided by the vacuum bag. Control joints were infused in the same manner but the steel substrate was not topographically modified with pins.

3.2 Low-Cost Method

A proprietary process has been developed that facilitates the attachment of small preformed pins to a metallic substrate. Initial work suggests that this alternative method at least matches the performance of ALM pins, while offering greater scalability and lower cost. The cost advantage is realised through lower processing/material costs, and considerably shorter process time. Except for high rate test specimens, which were made using the low-cost method, all hybrid joint data reported in this paper are based on specimens manufactured with ALM pins.

4 Experimental

4.1 Quasi-Static Testing

Quasi-static tests were carried out on the joints to obtain strength data and to compare failure mechanisms as a function of joint geometry (double-lap or single-lap) and reinforcing pin topology. Tests were carried out using an Instron 4507 testing machine operating at a crosshead displacement rate of 0.5 mm/min. Specimens were aligned parallel to the grip motion, resulting in predominantly mode-II loading across the joint region.

4.2 Fatigue Testing

A preliminary evaluation of the joint performance under cyclic loading was carried out. Tests were performed under load control, which meant that the machine compensated for the increasing specimen compliance due to crack growth. Loading was tension-tension, with the peak load equivalent to $0.5\sigma_u$, where σ_u was the ultimate joint strength evaluated by quasi-static tensile testing. A stress ratio of 0.1 was used and a test frequency of 3 Hz.

4.3 Drop-Weight Testing

Damage tolerance was evaluated by measuring residual strength after subjecting the joints to impact loading. An instrumented drop weight testing machine was used to apply the impact loads. This gave repeatable impacts, while also providing precise control of the damage location.

The sample set comprised 9 control and 9 hybrid joints with a sparse pin density of 1.24 pins/cm^2 over a joint area of 50 x 50 mm. Joints were subjected to impacts in the range 7 – 15 J using a 20 mm diameter hemispherical tup. The intention was to use a worst-case scenario and hence the impact site was biased toward the leading edge where the stress field is most conducive to damage propagation during subsequent loading. Furthermore, it seems plausible that the reduced pin reinforcement and stress concentration effects at the leading edge would result in visible damage at lower impact energies.

4.4 Environmental Conditioning

Hot-wet environmental ageing is known to degrade the performance of composite materials and adhesive bonds. A reduction in stiffness and peak strength can usually be linked to moisture absorption after sustained exposure to this type of environment [2]. For structural or other potentially critical multi-material joints, it is therefore necessary to evaluate performance under these conditions. An environmental chamber was used to provide an 'accelerated ageing' environment within the laboratory.

Six hybrid and three control joints, each of overlap area 25 mm x 25 mm, were set aside for these tests. The nine specimens were left inside the environmental chamber for over 3000 hours at 50 °C and 85% relative humidity.

4.5 High-Rate Tests

High rate tensile tests were conducted using a split-Hopkinson bar to compare the strength of hybrid and bonded joints. Five hybrid specimens and five control specimens were tested; each had a joint overlap area of 12.5 mm x 12.5 mm and a pin density of 4.48 pins/cm^2. Displacement data and failure sequence information were collected using high speed photography combined with Digital Image Correlation (DIC).

5 Results and Discussion

5.1 Quasi-Static Tests

Double lap hybrid joints with a uniformly dense reinforcement topology showed an improvement of 60% in short-term (quasi-static) strength compared to standard co-cured control samples. For these hybrid joints, failure was located in the composite adherend adjacent to the joint area. Modification of the reinforcement topology was made, with fewer pins toward the tip of the metal adherend. This was with the intention of reducing stress concentration caused by stiffness mismatch between the composite and the significantly stiffer joint overlap region.

Despite a small reduction in strength, this led to greater energy absorption, as indicated by the area under the load-displacement curve, prior to failure. The failure regime also changed from brittle-catastrophic failure of the composite adherend to a sequence of adherend disbonding, pin yielding and finally a combination of pin shearing and pull-out. An example of this latter failure type is shown in figure 2.

Further experimental investigations were subsequently conducted using single lap joint specimens. These tests showed increases in strength and energy absorption (compared with control specimens), in the range of 70-100% and 300-800%, respectively. It was noted that changes in the baseline strength of the adhesively bonded joint can have a significant effect on the resulting failure mode of the hybrid joints.

It appears that by controlling the relative strengths of the bonded interface and the reinforcing pins in the hybrid system, the failure mechanism may be manipulated. In cases where the bonded component of the overall joint strength was high, the observed failure was brittle and catastrophic. In cases where the strength of the pins was sufficient to carry load after disbonding, a progressive ductile failure was observed. In the latter case, it is equally important to ensure the reinforcement is not so strong that failure initiates in the composite adherend, which would be catastrophic.

5.2 Fatigue Tests

Joint damage under fatigue loading was assessed in terms of the change in joint compliance, which was inferred from the displacement of the machine crosshead when testing under load control.

In all cases, fatigue damage initiated at the bonded edges. Damage within the control joints progressed at an increasing rate following crack initiation. Damage in the hybrid joints initiated sooner, but the rate of damage growth reduced considerably as the crack front reached each row of reinforcing pins. Hybrid joints were able to survive at least as many cycles at $0.5\sigma_u$ compared with control joints, despite effectively being subjected to twice the load. Alternatively, it may be summarised that in the case of hybrid and control joints subjected to similar loads, hybrid joints will tolerate significantly more cycles prior to ultimate failure. It is expected that supplementary analysis and tailoring of the pin arrays may further enhance joint performance in fatigue loading.

5.3 Damage Tolerance

No delamination was observed within the composite substrates following impact; damage appeared to be limited to adherend disbonding and slight indentation/crushing at the impacted surface. Damage was assessed in terms of disbonded area, and residual strength was determined by quasi-static testing of the joints. Digital image processing was used to calculate disbonded area.

The impact energy required to generate visible damage was slightly higher for hybrid joints while the extent of disbonding at higher impact energies was reduced significantly. Figure 3 shows two specimens subjected to similar impact loading, one control and one hybrid joint and the greater extent of damage in the control joint (C9) compared to the hybrid joint (P8) is apparent. While damage was slightly asymmetric for C9, it is apparent for specimen P8 that the crack front has arrested in a smooth curve bound by a number of pins. This was found to be typical for the hybrid joints, and confirms the role of the pins in arresting disbonding.

Figure 4 shows a plot of post-impact residual strength against impact energy, while Fig. 5 shows the strength plotted against the corresponding disbonded area. It is clear that the hybrid joints suffered no significant loss in strength within the range of impact energies tested, even with up to 30% disbonded area (Figure 5). Control joints were shown to weaken significantly within the range of impact energies tested, for example, a 13 J impact was shown to give 42% disbonded area and an 18% strength reduction.

It is clear then that while the greater strength of the hybrid joints is due partly to the reduced disbonded area, by comparing hybrid and control joints with similar disbonded areas (the hybrid joint having experienced higher impact energy) the pinned joints still have significantly greater residual strength (Fig. 5). The implication is that, as well as being inherently stronger, the reinforced joints are much more damage tolerant.

The improvement in mechanical performance is a result of the load distribution across the joint. On a fracture mechanics argument, the disbonded area will propagate if the net stress intensity factor at the crack front exceeds a critical value. As long as the reinforcing pins bridge the two substrates, they are capable of transmitting load and therefore reduce stress intensity at the crack front. The stress intensity at the crack front will increase as the far field stress increases, or as the load bearing ability of the pins is reduced, e.g. as a consequence of pin fracture. The joint ultimately fails when the pins fracture at the base, or pull out of the composite.

Despite the high residual strength of the hybrid joints, it should also be recognised that this does not necessarily mean the full mechanical performance of the joint was retained. It was noted that compliance of the joints was affected by interface disbonding.

5.4 Environmental Conditioning

The level of moisture absorption was inferred from the change in mass of the joints over time. Figure 6 shows a typical example of mass change with respect to $\sqrt{t}$. The large drop off in moisture absorption is associated with a period where the water supply to the environmental chamber was interrupted, although the temperature was maintained. Once the water supply was restored the joints initially absorbed moisture at a higher rate before continuing to 3000 hours at a slower rate. The average mass gain for the composite adherend was 0.37%, though joints had not reached saturation after 3000 hours in the chamber. At the end of the ageing process, quasi-static shear strength was assessed as previously. It is expected that mechanical properties would continue to change in the manner discussed below, to the point where the joint was saturated.

Figure 7 shows the residual joint strength and energy absorption (approximated from the area under the load displacement curves) for conditioned and unconditioned joints. For standard co-cured control joints, strength reduced by around 21%, and energy absorption reduced by 35% as a result of the environmental ageing process. Hybrid joint strength and energy absorption reduced by an average of 17% and 11% respectively. Figure 7 also shows that, in these conditions at least, the aged hybrid joint exhibited greater strength and energy absorption than the as-manufactured control joint.

The apparent small reduction in energy absorption noted for hybrid joints was the result of a change in failure mechanism. These aged joints displayed varying levels of ductile failure, contrasting the brittle-catastrophic failure witnessed in quasi-static tests of un-aged joints from the same batch.

Figure 8 shows quasi-static results for similar aged and un-aged joints. A typical trace is shown for each type of joint. Aged hybrid joints showed a clear transition to multi-stage failure including adherend disbonding, pin yielding, pin pullout and pin fracture at the base of the pins. Despite a reduction in strength, further strain to failure following disbonding enabled aged hybrid joints to absorb almost as much energy as that recorded for the un-aged joints.

This change in behaviour was driven by a reduction in adhesive properties, and provides further support for the hypothesis made in section 5.1.

5.5 High-rate Testing

High rate testing was conducted with a typical input displacement rate of 2.5 m s^{-1}. Provisional results indicated that strength of the reinforced and standard bonded joints increased by 40% and 125% respectively when compared with the quasi-static data. Previous work suggested pinned and bolted composite lap joints may be weaker in high rate loading compared to quasi-static loading [3]. In contrast, it was suggested adhesive joints may show increased strength. The current work is consistent in demonstrating the increased strength of adhesive joints in high rate loading, and also showed a gain for hybrid joints. It is thought that the modest enhancement in the performance of hybrid joints under high rate loading is largely owed to the adhesive element. Despite the smaller increase in strength, hybrid joints provided the greatest overall strength in dynamic loading.

6 Conclusion

The hybrid method of joining fibre reinforced polymers to metals has been shown to enhance the mechanical properties of the joints, and to reduce sensitivity to damage caused by impact and degradation of the resin system.

The ratio of pin shear strength to adhesive shear strength was identified as being critical in predicting/designing the failure characteristics of hybrid joints, and may be modified through material selection or environmentally-induced degradation over time.

Additional fundamental work is required to investigate performance under cyclic and shock loadings. Furthermore, there is a need to test low-cost, scalable versions of the technology and performance in non-planar joint configurations.

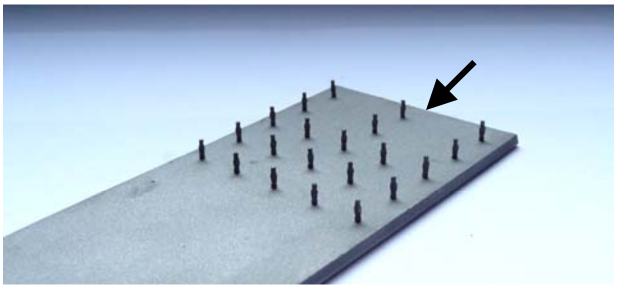

Figure 1 – ALM pins on metallic substrate, an arrow indicates the 'leading edge' of the joint.

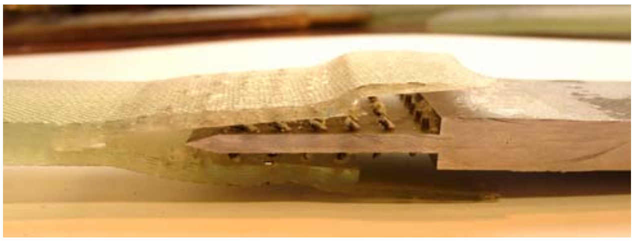

Figure 2 – A hybrid double lap joint following quasi-static tensile testing. Pin deformation is visible following the multi-stage failure sequence.

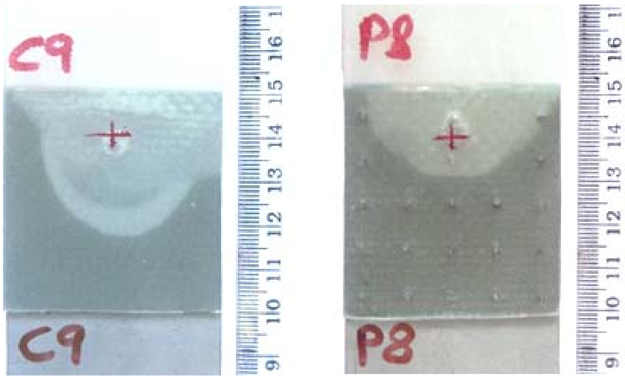

Figure 3 - Images showing the level of disbonding for a control and pinned joint after being subjected to a 13 J and 14 J impact respectively. The site of impact is the smaller region of damage close to the red target cross.

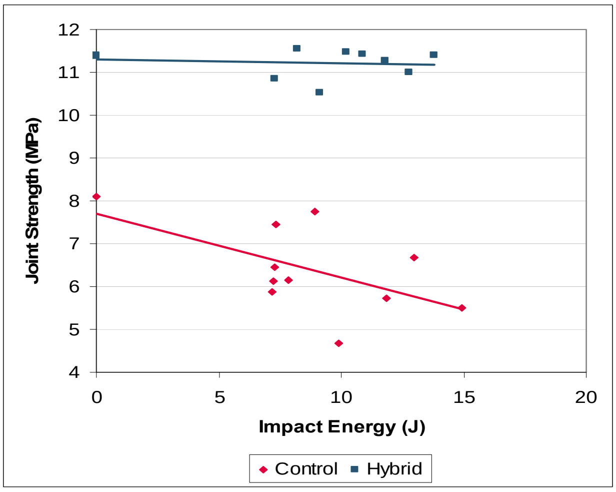

Figure 4 - Residual strength plotted as a function of impact energy for control and pinned specimens.

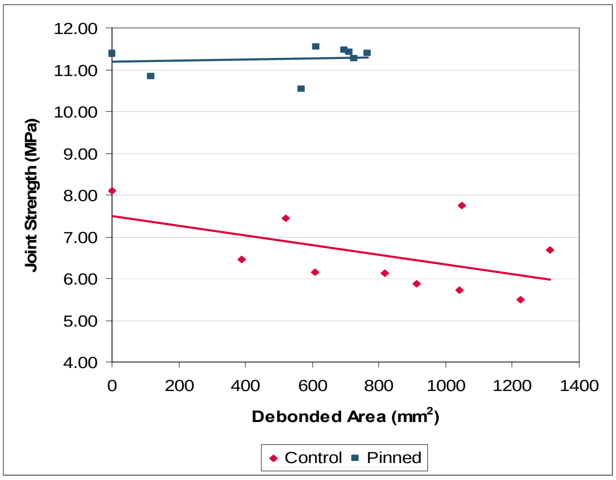

Figure 5 - Residual strength plotted as a function of disbonded area for control and pinned specimens.

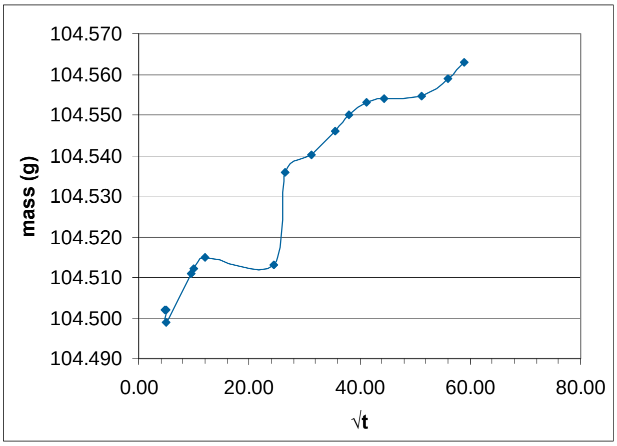

Figure 6 – A moisture uptake curve for control joint 'C4'. All joints tested had a similar curve. The large trough was caused by a period when the water supply to the environmental chamber was interrupted, although the temperature was maintained

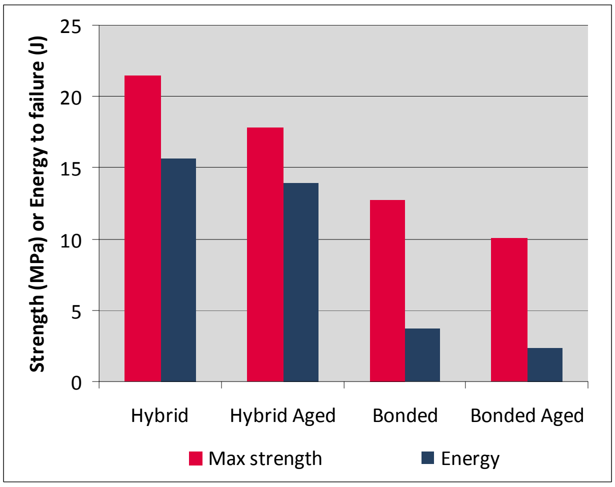

Figure 7 - Maximum shear strength and energy absorption for the environmentally conditioned joints, compared with un-aged joints.

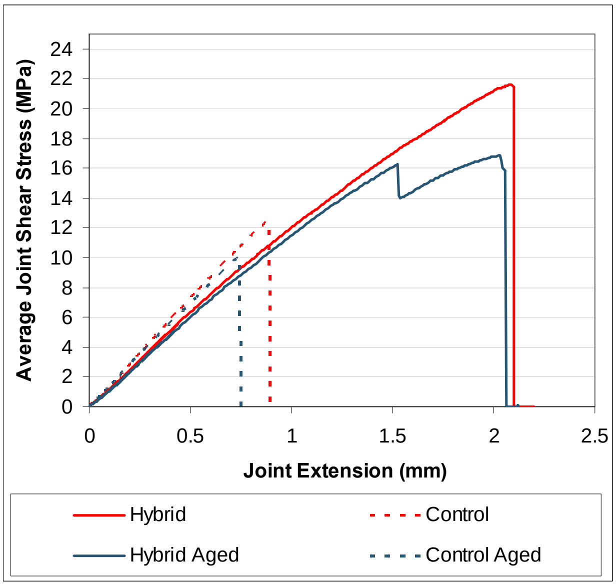

Figure 8 - Stress plotted against displacement for environmentally conditioned and as-manufactured joints.

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