FRACTURE AND FATIGUE PROPERTIES OF Z-PINNED COMPOSITE LAP JOINTS

P. Chang[1], A.P. Mouritz[1] and B.N. Cox[2]
[1] School of Aerospace, Mechanical & Manufacturing Engineering, RMIT University, VIC 3001, Australia
[2] Rockwell Scientific Co LLC, 1049 Camino Dos Rios, Thousand Oaks, CA 91360, USA

ABSTRACT

The effect of through-thickness reinforcement with z-pins on the static tensile properties, tensile fatigue life and failure mechanisms of single lap joints is experimentally investigated. Carbon/epoxy lap joints were reinforced in the overlap region with different volume contents (0-4%) and two sizes (0.28 & 0.51 mm diameter) of z-pins. Z-pins were found to be highly effective in increasing the ultimate strength, elongation limit and fatigue life of lap joints, with improvements in strength of over 40% being achieved. The optimum z-pinning characteristics to maximise the mechanical performance of joints were determined. Improvements to the static and fatigue properties were due to transitions in the failure mechanism from joint debonding in the absence of z-pins to pull-out or shear fracture of the z-pins or tensile failure of the laminate adherend, depending on the volume content and diameter of the pins.

1 INTRODUCTION

A long-standing problem with adhesively bonded joints made using fibre-reinforced polymer composite is failure of the bond-line due to over-loading, environmental degradation or fatigue. Bonded joints are particularly susceptible to delamination failure when subjected to in-plane tensile loading that imparts a shear stress along the polymer bond-line. A novel approach to increase the failure resistance of composite lap joints is to reinforce the bonded region with z-pins. Z-pinning involves inserting thin metallic or composite rods through the thickness of a composite, which can provide a large improvement to the shear strength of single lap composite joints [1,2], the pull-off strength of composite T-joints [3], and the fatigue life of bonded stiffeners on composites panels [4]. These improvements occur by the z-pins bridging across the fractured bond-line of a loaded joint, thereby transferring the applied stress across the joint region via a crack bridging mechanism.

Despite the improvement to the load-bearing properties of joints with z-pinning, the influence of the volume content and size of the z-pins on the static tensile properties and tensile fatigue life has not been systematically investigated to determine the optimum z-pinning conditions that provide the maximum improvement. Therefore, the aim of this study is to investigate the tensile properties and fatigue life of z-pinned single lap joints. The effects of the amount and diameter of z-pins on the strengthening and fatigue mechanisms of carbon/epoxy composite joints under static and fatigue loading is experimentally investigated. From this study, the z-pinning conditions needed to maximise the load-capacity and fatigue endurance of lap joints are determined.

2 MATERIALS & EXPERIMENTAL TECHNIQUES

2.1 Manufacture of Z-Pinned Lap Joints

Single lap joints were made using plain woven [0/90] carbon/epoxy prepreg (Fiberdux 914) supplied by Hexcel. Prior to curing, the joints were z-pinned through the overlap region using carbon/bismaleimide Z-Fibers^{TM} produced by Aztex Inc. The z-pins were inserted in the through-thickness direction using a hand-held ultrasonically actuated horn in a process described by Freitas et al. [5]. The influence of z-pin content on the tensile properties and fatigue life was examined by reinforcing the lap joint with thin (0.28 mm) diameter pins to volume contents of 0%, 0.5% (low), 2.0% (intermediate) and 4.0% (high). The effect of z-pin size was examined by reinforcing the joint using thin (0.28 mm) or thick (0.51 mm) diameter pins to the same volume content of 2.0%. After z-pinning, the lap joints were consolidated and cured in an autoclave at an overpressure of 500 kPa and temperature of 115^{o}C for one hour and then 750 kPa and 180^{o}C for two hours. The joints were bonded by co-curing of the adherends, and an adhesive was not used to increase the bond strength. The fibre volume content of the joints was ~62%, and was not affected significantly by the volume content or size of the z-pins. During insertion of the z-pins, subsequent cutting away of protruding ends of the z-pins by a shear blade, and then consolidation of the lap joints in the autoclave, a large number of z-pins became misaligned. The offset angle from the orthogonal (through-thickness) direction for the thin (0.28 mm) and thick (0.51 mm) diameter z-pins was measured to be 13.8 ± 4.2^{o} and 23.4 ± 4.5^{o}, respectively.

2.2 Tensile and Fatigue Testing of Z-Pinned Lap Joints

The ultimate strength and elongation limit of the lap joints was determined under axial tensile loading at a crosshead speed of 1 mm/min. The fatigue life of the joints was measured under tension-tension loading using a cyclic sinusoidal waveform with a stress (R) ratio of 0.6 and loading frequency of 5 Hz. Fatigue failure was taken to be when the joint could no longer carry the peak cyclic stress, which always coincided with complete rupture of the joint. Both the tensile and fatigue tests were performed using a 100 kN MTS machine under ambient environmental conditions (~22^{o}C, 50% relative humidity).

3 RESULTS & DISCUSSION

3.1 Tensile Properties of Z-Pinned Lap Joints

Figure 1 shows the effect of the volume content and size of the z-pins on the ultimate failure strength and elongation limit of the lap joint measured under static tensile loading. These properties are greatly improved with z-pinning. The properties do not increase progressively with z-pin content or diameter. Instead, the largest improvement occurs with the thin diameter z-pins at the intermediate volume content (2%), where the ultimate strength and failure limit are increased by 41% and 56%, respectively.

The joints were examined during and after tensile testing to determine the effect of z-pinning on the strengthening mechanics and failure mode. The failure mechanism was controlled by the z-pin content, with changes to the failure process occurring with an increasing amount of z-pin reinforcement, as shown in figure 2. Without z-pins, the unreinforced joint failed suddenly by unstable (rapid) crack growth along the bond-line (fig. 2a). At the lowest z-pin content (0.5vol%), the joint also failed along the bond-line, although the fracture process was more stable than in the unpinned joint specimen (fig. 2b). The z-pins were observed to bridge the debond crack, which allowed the applied load to be transferred across the crack. This toughening process was responsible for the improvement to the ultimate strength and elongation limit of the lightly pinned joint. At the ultimate failure stress the z-pins in the joint failed by shear rupture along the bond-line. A different failure mode was observed for the joints reinforced with the thin diameter z-pins to the intermediate (2%) or high (4%) contents. The bond-line cracks in these joints grew for a short distance (less than 5 mm) from the edges of the overlap region before being arrested due to the high toughness provided by the z-pins. These joints then failed in the laminate adherend near the edge of the overlap (fig. 2c). This clearly reveals that at the intermediate and highest amounts of z-pinning the bond-line strength exceeds that of the laminate adherend. Tensile studies have shown a monotonic deterioration of the static strength of carbon/epoxy laminates with increasing z-pin content due to an increased volume density of crimped and distorted fibres together with resin-rich regions near the z-pins [5,6]. This loss in the laminate strength combined with the increased toughness of the bonded region accounts for the transition in the failure mode from the bond-line to the adherend. The strength of the lap joint was maximised at the point when this transition in failure mechanism occurred, which for the thin z-pins was between 0.5 and 2.0 vol%.

The tensile properties and failure mode of the joints were also controlled by the pin diameter. As mentioned, at a volume content of 2% the thin z-pins suppressed large-scale cracking along the bond-line, and this caused the joint to fail in the laminate adherend (fig. 2c). In contrast, the joint reinforced with the thick z-pins failed at the bond-line, even though the volume content of pins was the same (fig. 2d). Before failure, a large-scale z-pin bridging zone developed behind the crack front that allowed the joint to withstand increased loading beyond the bond-line failure strength. At the ultimate failure stress the thick z-pins failed by transverse (shear) rupture and/or pull-out.

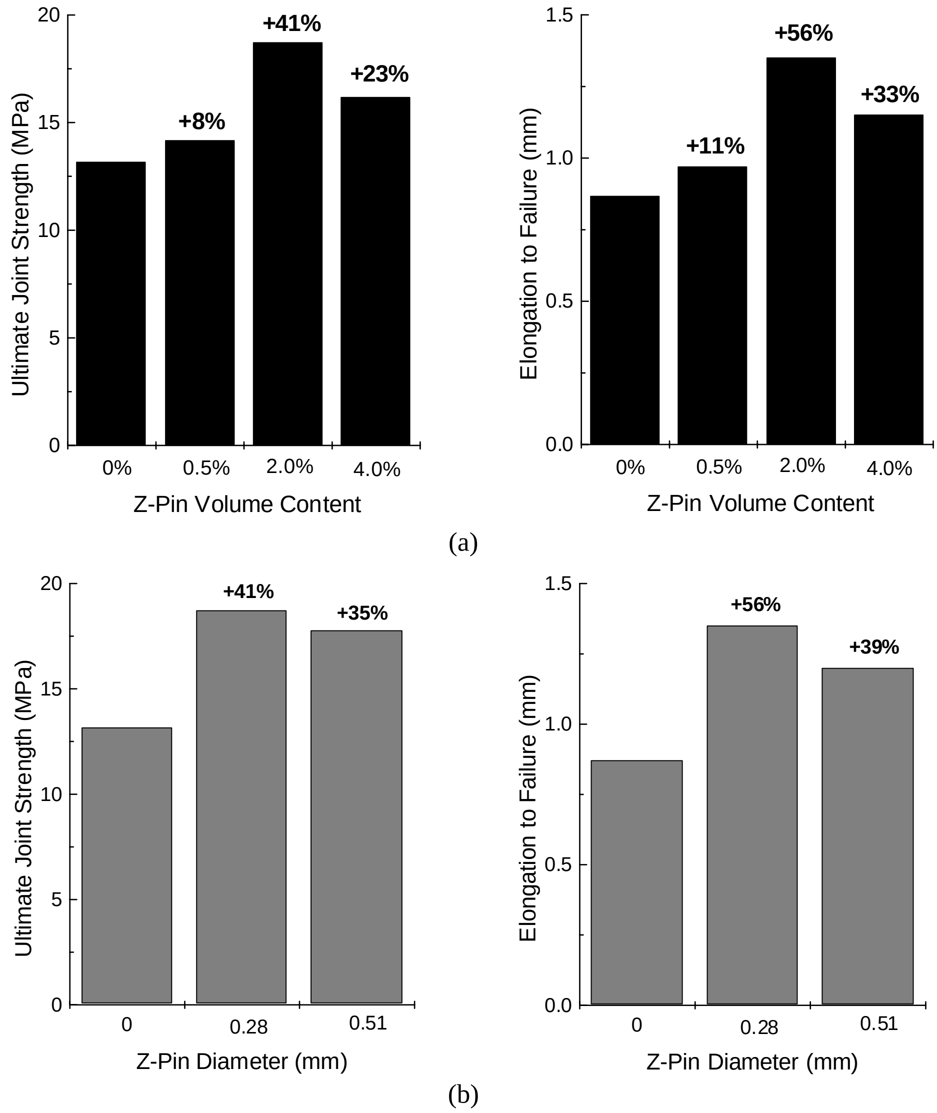


Figure 1: Effect of (a) volume content and (b) diameter of z-pins on the failure strength and elongation limit of the lap joint.

No Z-Pins: *Unstable Bond-Line Fracture*

Low Z-Pin Content (0.28 mm ϕ): *Stable Bond-Line Fracture with Z-Pin Shear Rupture*

Intermediate & High Z-Pin Contents (0.28 mm ϕ): *Laminate Failure*

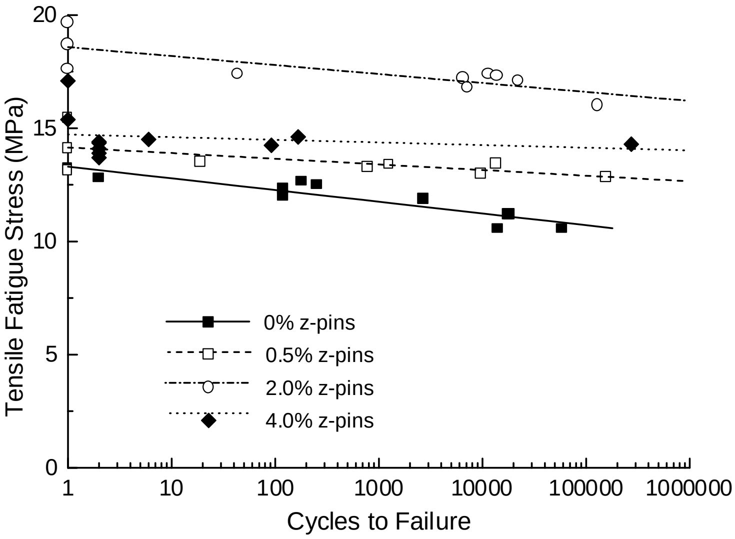
Intermediate Z-Pin Content (0.51 mm ϕ): *Stable Bond-Line Fracture with Z-Pin Rupture & Pull-Out*

Figure 2: Failure modes of the unpinned and z-pinned lap joints.

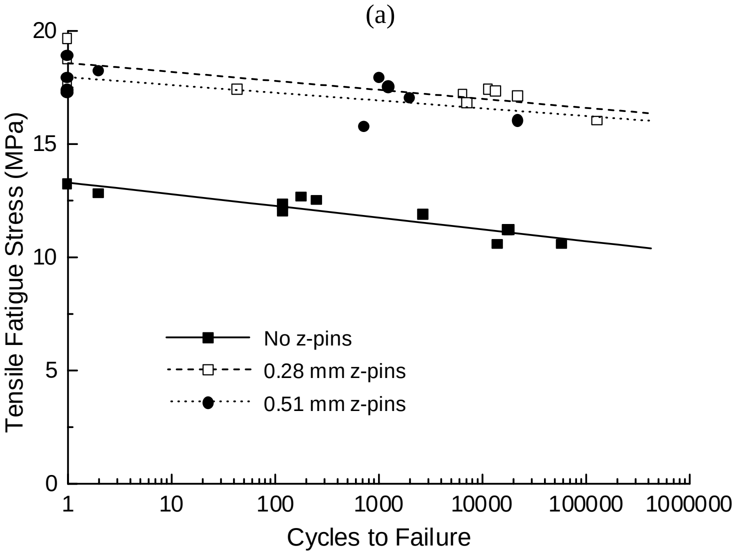
3.2 Fatigue Properties of Z-Pinned Lap Joints

The effect of the volume content and diameter of z-pins on the tensile fatigue life (S-N) curve for the lap joint is shown in figure 3. The fatigue life increased rapidly with the volume content of z-pins, although the maximum fatigue resistance was attained at a pin content of 2% rather than 4%. This trend is the same to that found for static tensile strength, where the ultimate strength was higher at the intermediate rather than highest pin content. Similarly, the fatigue life of the joint was slightly superior when reinforced with thin rather than thick pins, which is a similar trend to that observed for the static tensile properties.

The fatigue damage process and failure mode of the unpinned and pinned joints was examined during testing. It was observed that the joint without z-pins failed under fatigue loading by cracking along the bond-line. This is the same failure mode that occurred under static tensile loading (see fig. 2a). Likewise, the joint reinforced with the lowest volume content (0.5%) of z-pins failed along the bond-line, and again the same failure mode occurred under static loading (fig. 2b). In this joint the crack grew slowly along the bond-line with an increasing number of fatigue load cycles. This led to the development of a large-scale bridging zone behind the crack front that transferred the applied fatigue stress between the delaminated surfaces, and this mechanism was responsible for the increased fatigue life of the joint with the lowest pin content. The z-pins in this joint eventually failed by fatigue-induced transverse (shear) rupture along the bond-line. Two different fatigue failure mechanisms were observed for the joint reinforced with 2.0% z-pins. The first failure mechanism of this joint involved fatigue-induced rupture of the laminate adherend, and the failed joint appeared similar to that shown in fig. 2c. The second mechanism involved stable crack propagation leading to the formation of a bridging zone that eventually failed by pull-out and rupture of the z-pins, and appeared similar to the specimen shown in figure 2d. This failure mode was not observed under static tensile loading. The presence of two competing mechanisms suggests that the fatigue properties of the bridging zone and the laminate adherend are virtually identical at the intermediate pin content. Only the lap joint reinforced with a z-pin content of 4% did not experience fatigue-induced failure at the bond-line. Instead, failure of this joint occurred by tensile fatigue rupture of the laminate adherend. It is believed that an excessive amount of fibre distortion caused by the high amount of z-pins reduced the fatigue life of the laminate below the endurance limit of the bonded region in this joint.



(a)



(b)

Figure 3: Effect of (a) volume content and (b) diameter of z-pins on the S-N curve for the lap joint.

The fatigue mechanism of the lap joint was affected by the pin diameter in some cases. The joints reinforced with the thick pins failed by stable delamination crack growth along the bond-line with an increasing number of load cycles, which led to the formation of a large scale crack bridging zone which carried the applied fatigue stress. Eventually failure of the z-pins occurred by pull-out and transverse fracture (fig. 2d). However, the joint with the thin z-pins experienced two competing failure mechanisms: pull-out and fracture of the z-pins or fatigue-induced rupture of the laminate adherend.

ACKNOWLEDGMENTS

This research was performed with financial support provided by the Australian Research Council (Grant No. DP0211709). PC thanks the CRC for Advanced Composite Structures Ltd. for the provision of a scholarship. BNC was supported by the U.S. Dept. of Energy (Grant No. DE-FG03-97ER45667).

REFERENCES

1. Rugg KL, Cox BN, Ward KE, Sherrick GO. Damage mechanisms for angled through-thickness rod reinforcement in carbon-epoxy laminates, Comp., Vol. 29A,1603-1613, 1998.
2. Rugg KL, Cox BN, Massabò R. Mixed mode delamination of polymer composite laminates reinforced through the thickness by Z-fibers, Comp., Vol. 33A,177-190, 2002.
3. Freitas C, Fusco T, Campbell T, Harris J, Rosenberg, S. Z-fibre Technology and Products for Enhancing Composite Design, in Proc. 83th AGRAD Conference, Paper 17, 1996.
4. Owsley GS. The effect of Z-fiber™ reinforcement on fatigue properties of stiffened blade panels, Proc. 15th Tech. Conf. American Comp. Soc., Texas, 25-27 Sept. 2000.
5. Freitas G, Magee C, Dardzinski P, Fusco T. Fiber insertion process for improved damage tolerance in aircraft laminates, J. Adv. Mats., Vol. 25, 36-43, 1994.
6. Chang P, Mouritz AP, Cox BN. Tensile fatigue properties of z-pinned carbon/epoxy composite, Proc. 49th SAMPE 2004 Symp. & Exhib., Long Beach CA, May 16-20, 2004.