DAMAGE TOLERANCE OF Z-PINNED COMPOSITE JOINTS

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Keywords: *composites, pins, through-thickness reinforcement, joints, damage*

Abstract

This paper presents an experimental study into the improvement to the damage tolerance of T-shaped stiffened carbon fibre/epoxy joints when reinforced with thin z-pins. Joint pull-off tests revealed that the ultimate failure load and absorbed energy capacity of the skin-to-stiffener flange connection increased rapidly with the volume content of z-pins due to suppression of bond-line cracking. Improvements to the ultimate load and absorbed energy capacity of over 75% and 600%, respectively, was achieved when the joints were reinforced at the relatively modest z-pin content of 4% by volume. Experimental analysis also showed that z-pins were highly effective at improving the damage tolerance of T-joints that contained a single bond-line delamination crack or multiple cracks along and near the bond-line caused by impact loading. The residual mechanical properties of damaged z-pinned joints were much higher (typically in the range of 100 to 500%) than of the unpinned joint. Based on this research z-pinning is shown to be an effective technique for increasing the damage tolerance of composite joints for load-bearing structural applications.

1 Introduction

Thin-skin composite panels used in load-bearing aircraft structures and other light-weight structural applications are stiffened to increase their buckling strength under in-plane compression loading. The panels are stiffened with T, L or C-shaped stiffeners (e.g. ribs, stringers, spars, etc.) which are bonded to the skin by co-curing or an adhesive. Stiffened panels for aircraft structures must support the design limit load when damaged by over-loading, impact, environmental deterioration or some other damaging event. However, a problem with many types of stiffened composite panels is their low damage tolerance due to their susceptibility to rapid delamination cracking (so-called "unzipping") between the skin and stiffeners. In this paper, damage tolerance is defined as the capacity of T-joints to maintain their structural properties in the presence of damage. The low damage tolerance is due mainly to the low strength and low fracture toughness of the bond-line that connects the stiffener flanges to the skin. Long delamination cracks can grow unstably along the weak bond-line which leads to a large loss in the strength of composite joints [e.g. 1-4]. Various methods have been used to increase the damage tolerance of composite joints, including using toughened adhesives or over-designing (which adds weight). Unfortunately, however, most strengthening methods provide only an incremental (rather than large) improvement to the ultimate load of joints.

Experimental and numerical research studies have shown that the through-thickness reinforcement of bonded composite joints with z-pins is a highly effective method for improving the structural properties [5-16]. Z-pins are thin fibrous composite or metal rods that are inserted in the through-thickness direction of laminates or sandwich materials [e.g. 17,18]. It has been proven that z-pins are highly effective at increasing the ultimate failure strength, absorbed energy, and fatigue life of bonded composite joints by generating bridging traction loads across the fractured bond-line which resist large-scale delamination crack growth [5-16].

While the capacity of z-pins to increase the mechanical properties of bonded composite connections (including lap, T- and L-shaped joints) without damage has been proven [5-16], there is no published work into the improvement to the damage tolerant properties of joints by z-pinning. To date, research has centered on the analysis and experimental determination of the mechanical properties and strengthening mechanisms of z-pinned joints without pre-existing damage [5-16]. No work has been reported on the capacity of z-pins to improve the damage tolerance of joints that contain pre-existing defects such as delamination cracks or impact-induced damage. Several studies [17-22] have shown that z-pinning is an effective method for increasing the impact damage resistance and post-impact compression properties of flat composite panels, but similar work on joints has not been reported.

This paper presents an experimental investigation to determine the effect of z-pinning on the damage tolerant properties of composite T-joints. The effect of increasing volume content of z-pins (up to 4%) on the structural properties and strengthening mechanisms of T-joints without damage was determined under tensile (pull-off) loading. This loading case was selected because it is sensitive to changes in the mechanical properties caused by defects and damage at the bond-line. The effect of z-pins on the residual structural properties of T-joints containing a single bond-line delamination crack of different lengths (between 5% and 100% of the skin-stiffener flange bonded region) was experimentally determined. This study was aimed at quantifying the improvement to the residual load capacity of joints containing a single dominant bond-line crack caused by poor manufacturing or over-loading. The effect of z-pins on the damage tolerance of joints containing different amounts of impact damage was also investigated. The objective of this testing was to determine the damage tolerance of z-pinned joints used in aircraft structures when impacted by a bird, dropped tool or some other impact loading event.

2 Materials and Experimental Techniques

2.1 Materials

The geometry of the composite T-joint specimen used to assess the capacity of z-pins to improve the structural and damage tolerant properties is shown in Fig. 1. The specimen has the typical shape of bonded T-stiffeners used to increase the buckling resistance of thin-skinned composite panels used for aircraft structures. T-joints were fabricated using unidirectional T700 carbon fibre/epoxy prepreg tape (Advanced Composites Group, VTM264) which was stacked in a $[90/0]_s$ ply sequence for both the skin and stiffener. The stiffener and skin were each 2 mm thick, and their bonded region was 100 mm long and 25 mm wide. The Δ-fillet region at the stiffener base was filled with unidirectional prepreg tape to avoid the formation of a resin-rich zone during curing.

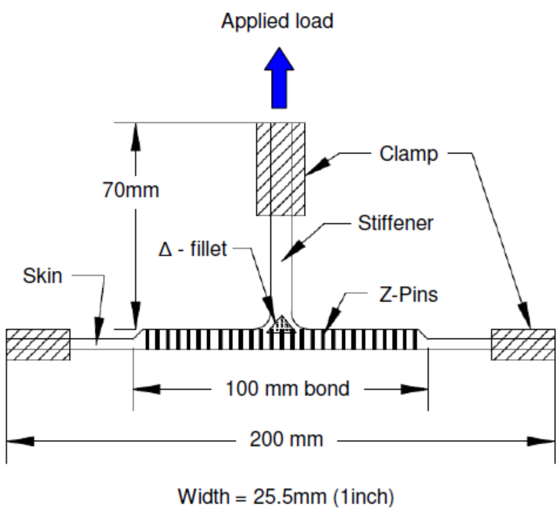


Fig. 1. Schematic of T-joint specimen reinforced with z-pins. The dimensions, boundary (clamping) conditions, and load direction are indicated.

Before curing of the T-joints, the entire bond region connecting the skin and stiffener flange was reinforced in the through-thickness direction with z-pins, as indicated in Fig. 1. The composite material outside of the bonded region was not pinned. The z-pins were pultruded rods of T300 carbon fibre/bismaleimide with a diameter of 0.28 mm, and they were supplied by Albany Engineered Composites Pty. Ltd. The z-pins were inserted into the joint from the skin side using the UAZ process, which basically involved driving the pins through the uncured skin-to-stiffener flange connection using an ultrasonic device which generated high frequency (20 kHz) compressive waves. Koh et. al. [15] give a detailed description of the z-pinning process used to reinforce the T-joints. The joints were reinforced with z-pins to volume contents of 0.5%, 2% or 4%. The z-pins were arranged in a square grid pattern with the rows of pins aligned parallel and transverse to the lengthwise direction of the skin-stiffener connection. In addition, a control joint without z-pins was produced. The unpinned and z-pinned joints were cured and consolidated in an autoclave at 120°C and 620 kPa for one hour. The skin and stiffener flange were bonded by co-curing without film adhesive. The average volume content of carbon fibres in the fully cured skin and stiffener sections of the T-joints was about 60%.

Pristine T-joint specimens (without pre-existing damage) were tested to determine the influence of z-pins on the structural properties and strengthening mechanisms. Joints without z-pins or with z-pins at volume contents of 0.5%, 2% or 4% were tested. In addition, the structural properties of T-joints containing a single bond-line crack along the skin-stiffener flange connection were determined (see Fig. 2). The properties of the pre-cracked joint without z-pins were compared against the pre-cracked joint with 2% z-pins. The crack in these joints was created by inserting 5 μm thick non-stick PTFE film along the bond-line before co-curing of the skin and stiffener within the autoclave. The pre-crack was centered below the stiffener and extended for lengths between 5 mm (or 5% of the bonded region) and 100 mm (100%) along the skin-stiffener flange connection. This damage simulated different amounts of delamination cracking along the bond-line of T-joints caused by poor quality manufacturing or over-loading during service.

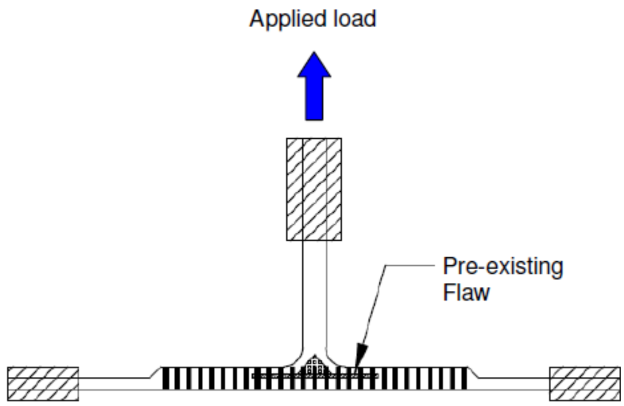


Fig. 2. Schematic of T-joint specimen reinforced with z-pins containing a single bond-line crack.

The damage resistance and residual properties of the T-joint following impact loading was also determined. Impact tests were performed by dropping a 12 mm diameter hemispherical steel tup (1.5 kg) on the skin immediately above the stiffener, as shown schematically in Fig. 3. The impact machine was instrumented with a laser photo/diode system to measure the amount of energy absorbed by the joint specimen during the impact event. Impact tests were performed over a range of incident energy levels from 1 J (which did not cause damage) to 18 J (which caused complete failure). Following testing, the specimens were inspected using an ultrasonic C-scan system (frequency of 10 MHz) to measure the size of the impact damaged region. Impact tests were performed on T-joints without z-pins or 2% pin content.

The mechanical tests of the T-joint specimens were measured by applying a tension force to the stiffener using a 50 kN Instron machine, as indicated in Fig. 1. The edges of the skin were clamped to a rigid support plate, and then an axial pull-off load was applied to the stiffener end at a constant displacement rate of 1 mm/min until complete failure. At least three samples were tested under identical conditions to determine the scatter in the measured property values. It is important to note that all values obtained from the pull-off test are considered 'apparent' property values because they are dependent on the specimen geometry and the loading test conditions. However, the testing does provide property data which can be used to identify trends for the structural and damage tolerant properties of T-joints when reinforced with z-pins.

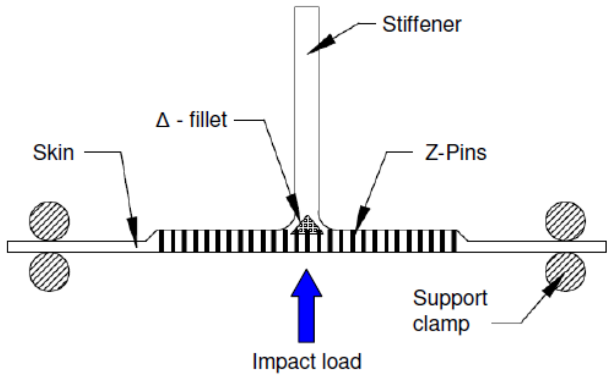


Fig.3. Schematic of T-joint specimen reinforced with z-pins subjected to impact loading.

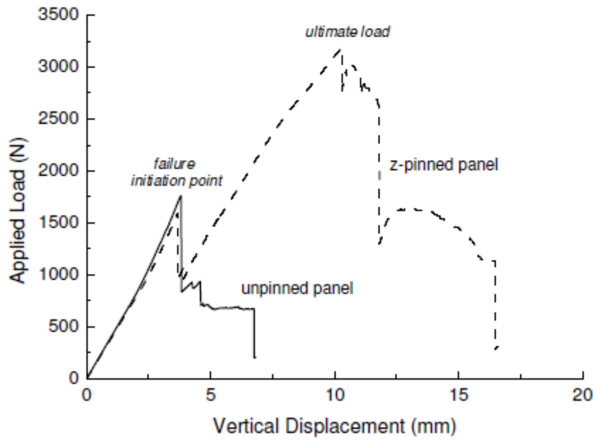


Fig. 4. Applied load-displacement curves for the defect-free T-joint with and without z-pins. The z-pinned joint had a pin content of 2% by volume.

3 Results and Discussion

3.1 Structural Properties of Damage-Free Joints

Fig. 4 shows applied pull-off force-displacement curves for the damage-free T-joint with and without z-pins. The curve presented for the z-pinned specimen is the joint with the intermediate volume content of pins (2%). Curves with similar profiles were measured for the joints reinforced at the low (0.5%) or high (4%) pin contents. Fig. 4 shows that an initial load drop occurred at an applied force of about 1600 N for both the unpinned and z-pinned joints, and this defined the point of first failure. Failure initiated in the Δ-fillet region, which finite element analysis shows is the region of highest stress concentration for the pull-off load condition [24]. At the point of first failure the load capacity of the unpinned joint dropped abruptly due to unstable propagation of a delamination crack along the centre-line of the stiffener as well as along the bonded region between the skin and stiffener flange. In contrast, the load capacity of the z-pinned joint decreased slightly and then immediately recovered to carry increased load due to the resistance imposed by the z-pins against large-scale delamination cracking.

The large-scale damage suffered by the unpinned joint and the much smaller amount of damage experienced by the z-pinned joint at the point of first failure is shown in Fig. 5. It is well known that z-pins generate bridging traction loads across delamination cracks, and thereby oppose large-scale crack growth by promoting high interlaminar fracture toughness [e.g. 25-30]. For this reason, the joint reinforced with z-pins did not rupture at the initiation point of first failure, unlike the unpinned joint that failed catastrophically by rapid delamination crack growth.

The ultimate load and absorbed energy capacity of the T-joints increased with the volume content of z-pins, as shown in Fig. 6. The ultimate load is the maximum force the joint can withstand under applied pull-off loading whereas the absorbed energy capacity is the total amount of elastic and inelastic strain energy absorbed by the joint under load, and is determined by the area under the applied force-displacement curve, limited by complete disbonding of skin and stiffener. Fig. 6 shows that both the maximum load and absorbed energy capacity of the joint increased rapidly with the z-pin content. This agrees with previous studies that report large improvements to the mechanical properties of lap-, T- and Ω-shaped bonded joints due to z-pinning [5-16].

The maximum load and energy absorption of the T-joints studied here was increased by bridging traction loads generated by the z-pins, which involved elastic stretching, frictional pull-out and, in some cases, rupture of the pins [15]. The total bridging traction load increases with the volume content of z-pins [25-30], which is the reason for the rapid increases to the ultimate load and absorbed energy capacity.

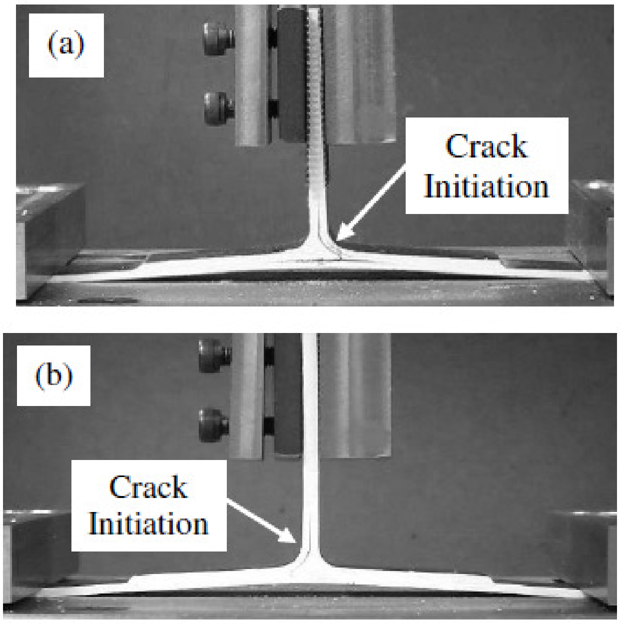


Fig. 5. Damage in the defect-free T-joints (a) without z-pins and (b) with z-pins when loaded to the failure initiation stress. The z-pinned joint had a pin content of 2% by volume.

Post-mortem examination of the T-joint specimens after testing revealed that the final fracture mode was controlled by the volume content of z-pins. The unpinned joint and the joints reinforced at the lowest (0.5%) and intermediate (2%) z-pin contents failed by delamination cracking along the bonded region between the skin and stiffener flange. The joint with the highest z-pin content (4%), however, failed within the laminate material outside of the bonded region. This change in the failure mode was due to the bridging traction load generated at the highest z-pin content exceeding the rupture load of the carbon/epoxy material used in the joint. Failure of the laminate material, rather than the bonded region between the skin and stiffener flange, indicates that maximum possible strengthening of the T-joint was achieved at the highest z-pin content.

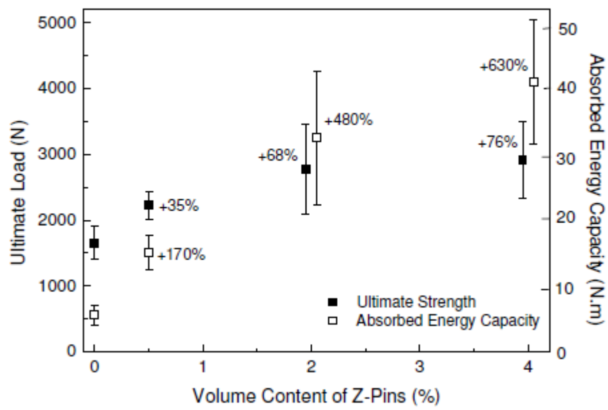


Fig. 6. Effect of volume content of z-pins on the ultimate strength and absorbed energy capacity of the defect-free T-joint. The percentage increase to the property values due to z-pinning are given.

3.2 Damage Tolerance of Z-Pinned Joint Containing Bond-Line Delamination Crack

This section presents experimental research into the damage tolerance of the z-pinned joint that contains a single bond-line crack (Fig. 2). As mentioned, this represents the damage that occurs due to inferior manufacturing which results in poor adhesion or in-service over-loading of the joint. Fig. 7 shows the typical effect of z-pin reinforcement on the applied force-displacement curve for the joint when a pre-existing delamination crack was present. This figure shows the curves for a 20 mm long crack in both the unpinned and z-pinned joints, and differences between the two joints were determined for the other crack lengths. The load-bearing capacity of the joint was greatly improved by z-pinning, which reveals that this strengthening method is effective for increasing the damage tolerance of T-joints against bond-line cracks.

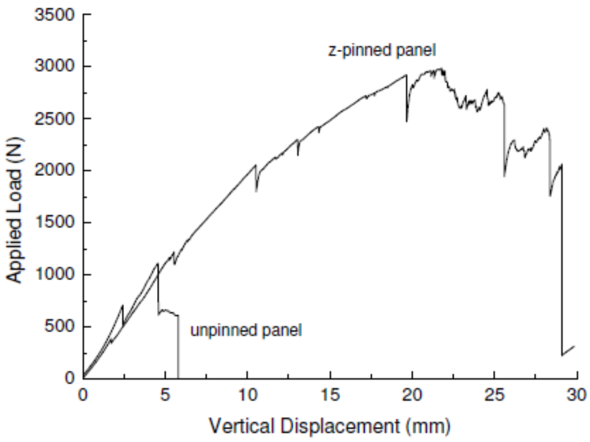


Fig. 7. Applied load-displacement curves for the T-joints with and without z-pins containing a pre-existing 20 mm long delamination crack. The z-pinned joint had a pin content of 2% by volume.

Fig. 8 shows the effect of increasing initial crack length on the ultimate load and absorbed energy capacity of the unpinned and z-pinned joints. The structural properties of the unpinned joint decreased steadily with increasing initial crack size due to the reducing size of the bonded region between the skin and stiffener flange. The ultimate load and absorbed energy capacity of the z-pinned joint were much higher than the unpinned joint for all crack lengths, which demonstrates the high damage tolerance that can be achieved by z-pinning. Due to the large scatter in the property values for the z-pinned joint specimens, it is difficult to state conclusively that the ultimate load and absorbed energy capacity are independent or decrease gradually with increasing initial crack length. Unlike the unpinned joint that shows a statistically significant trend of decreasing mechanical properties with increasing initial crack length, the same cannot be concluded for the z-pinned joint due to the large amount of variability in the measured property values. Despite this scatter, however, the results clearly show that z-pinning increased greatly the properties for the T-joint containing a pre-existing crack, even for long crack lengths.

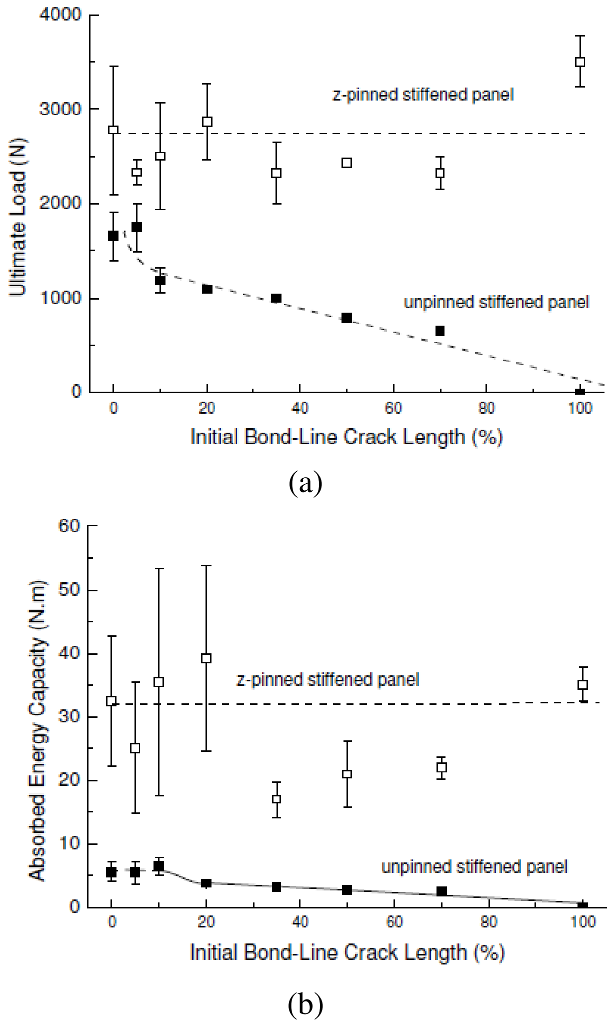
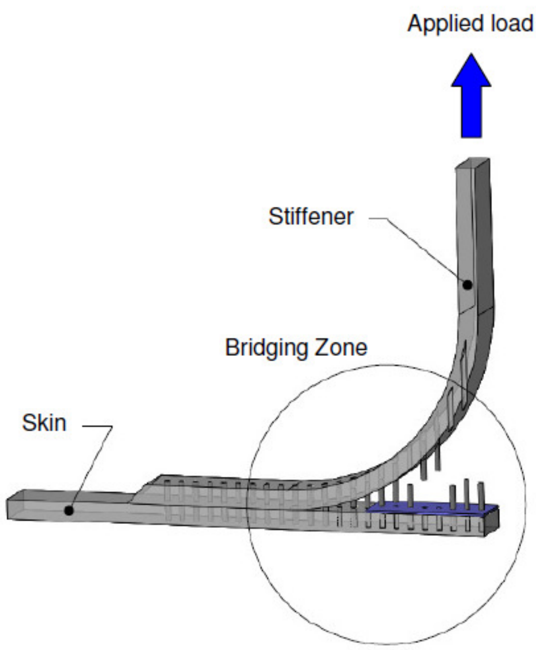


Fig. 8. Effect of initial pre-crack length (expressed as a percentage of the total bonded length between the skin and stiffener) on the (a) ultimate strength and (b) absorbed energy capacity of the unpinned and z-pinned T-joints. The z-pinned joint had a pin content of 2% by volume.

The scatter to the ultimate load and, in particular, absorbed energy capacity of the T-joint was increased greatly by z-pinning. The cause of this scatter is attributed to the variability in the inclination angles of the z-pins in the skin/stiffener flange connection and the variability in the bond strength between the pins and laminate due to interfacial cracking. Koh et al. [31] recently showed that these induce a large amount of scatter to the traction load and traction energy generated by a single z-pin during pull-out from the laminate substrate. Indeed, one of the problems with z-pin reinforcement is the intrinsically high amount of scatter in material properties due to microstructural defects introduced into the laminate during manufacturing [18].

The T-joint specimens containing the pre-existing crack failed by the generation of a bond-line peeling (crack opening) stress, as shown schematically in Fig. 9. The crack opening displacement increased with distance behind the crack tip. The stiffness of the joint was not affected significantly by the initial crack length, and therefore the bending moments generated in the skin and stiffener flange laminates were independent of the pre-crack length. As a result, the number of z-pins that carried the applied force within the bridging traction zone was independent of the initial crack size. As cracking progressed along the bond-line, irrespective of the initial crack length, the number of bridging z-pins remained approximately constant. Consequently, the maximum load and the absorbed energy capacity of the z-pinned joint not reduced significantly with increasing initial crack length and therefore the pins appear equally effective at promoting high damage tolerance against both small and large cracks.



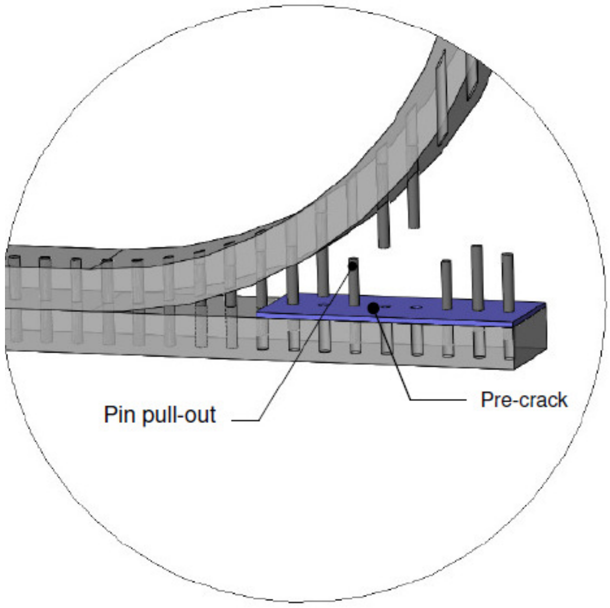


Fig. 9. Schematic of the crack opening displacement and z-pin bridging traction zone in a T-joint containing a pre-existing crack. The length of the bridging traction zone was not dependent on the initial pre-crack length.

3.3 Damage Tolerance of Z-Pinned Joint Containing Impact Damage

This section reports on the research work performed to experimentally assess the impact damage tolerance of the T-joints reinforced with z-pins. The joints were impacted on the skin immediately above the stiffener at different energy levels (Fig. 3). Fig. 10 shows the effect of increasing incident impact energy on the percentage of the skin-stiffener flange bonded region which was delaminated in the unpinned and z-pinned joints. The amount of delamination damage to the impacted joints was measured using through-transmission ultrasonics. Damage in both the unpinned and z-pinned joints initiated in the Δ-fillet region at a low energy level (~2 J). It is well known that z-pinning does not increase the load to initiate delamination cracks in composite materials [6,18,25], which is the reason for the z-pinned and unpinned joints having the same impact energy for damage initiation. However, large differences in the amount of impact-induced delamination damage at the skin-stiffener flange connection were measured between the joints at higher impact energy levels.

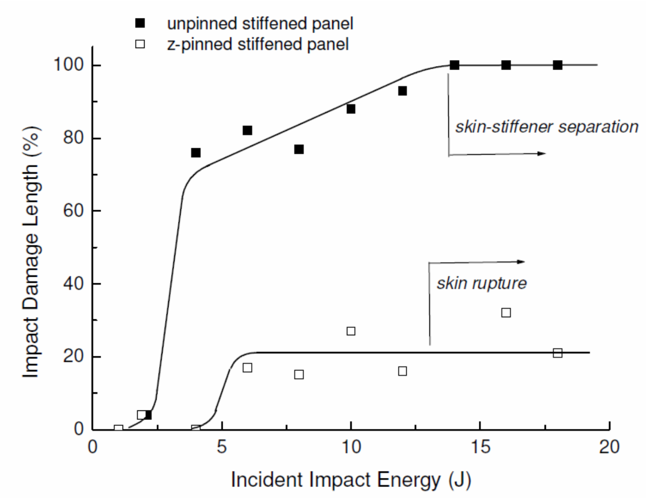


Fig. 10. Effect of incident impact energy on the delamination crack length in the unpinned and z-pinned T-joint. The delamination length is expressed as a percentage of the total bonded length (100 mm). The z-pinned joint had a pin content of 2% by volume.

The amount of impact damage to the unpinned joint increased sharply between 2 and 4 J due to large-scale delamination crack growth along the skin-stiffener connection. For example, Fig. 11 shows the damage suffered by unpinned joint specimens when impacted at intermediate (8 J) and high (14 J) energy levels, and there is extensive cracking between the skin and stiffener flange. The amount of delamination damage increased gradually from about 80% of the bonded region at 4 J to 100% (i.e. complete skin-stiffener flange separation) at 14 J. This behavior shows the low impact damage resistance of the unpinned joint. In contrast, the amount of damage suffered by the z-pinned joint was much less (under ~20% of the bonded region) until the impact energy exceeded 14 J when the skin ruptured without complete separation of the stiffener flange from the skin, as shown in Fig. 12. Several studies [19-22] have reported reductions in the amount of impact-induced damage to flat laminate panels when reinforced with z-pins, and the results presented in figure 13 show that large improvements to the impact damage resistance can also be achieved in T-joints by z-pinning.

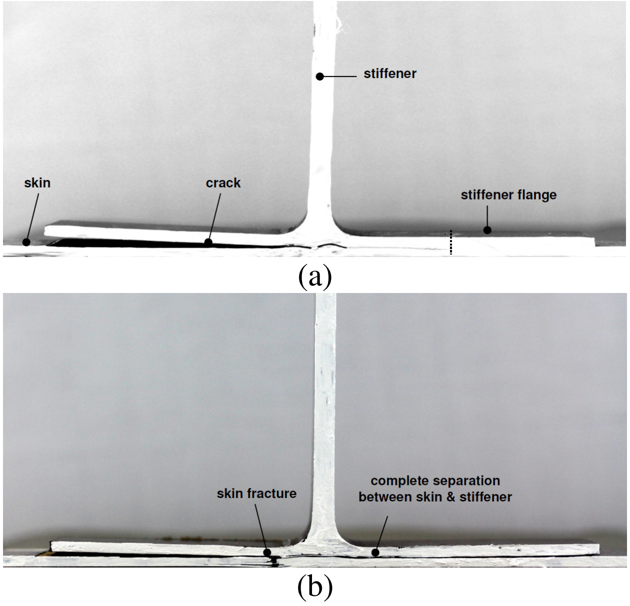


Fig. 11. Unpinned T-joint specimens following impact loading at energy levels of (a) 8 J and (b) 14 J.

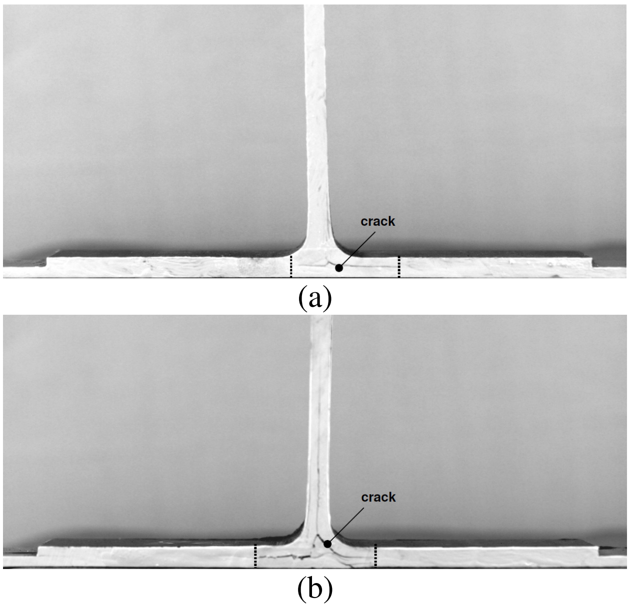


Fig. 12. Z-pinned T-joint specimens following impact loading at energy levels of (a) 8 J and (b) 14 J.

The effect of increasing impact energy on the residual pull-off load of the T-joints is shown in Fig. 13. The post-impact strength of the unpinned joint dropped sharply between 2 and 4 J due to the large and abrupt increase in the amount of impact damage. The residual load capacity remained at a low value (~15% of the original strength) over the impact energy range of 4 – 12 J, above which the skin separated completely from the stiffener flange. In contrast, the post-impact strength of the z-pinned joint decreased steadily with increasing impact energy up to 14 J, at which point the skin broke. The post-impact load capacity of the z-pinned joint was much higher than the unpinned joint. Also, the steady (controlled) reduction to the post-impact strength of the z-pinned joint, as opposed to the large and sudden loss in strength for the unpinned joint, demonstrates the superior impact damage tolerance. Figure 14 also shows that the z-pinned joint retained some residual strength at impact energy levels above 14 J (when the skin was broken) whereas the unpinned joint had no post-impact strength, which further proves the impact damage tolerance gained by z-pinning.

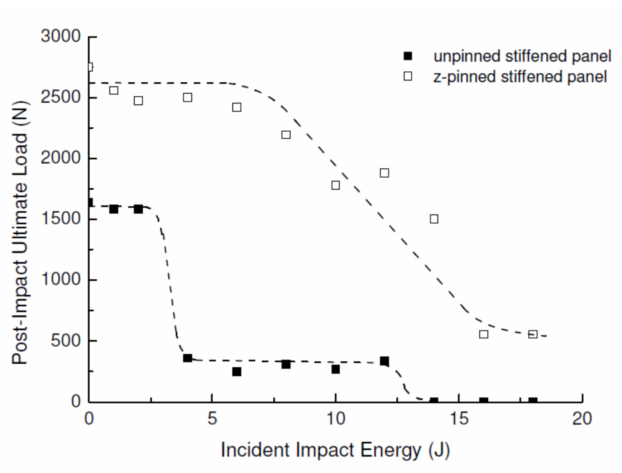


Fig. 13. Effect of incident impact energy on the post-impact ultimate load of the unpinned and z-pinned joints. The z-pinned joint had a pin content of 2% by volume.

It is interesting to note that the ultimate load of the z-pinned joint was reduced by high energy impact loading (figure 13) whereas the load capacity of the same joint was not reduced by bond-line cracking (figure 11). Impact loading of the z-pinned joint caused longitudinal splitting along the stiffener laminate as well as delamination cracking between the skin and stiffener flange. The amount of damage to the stiffener increased with the impact energy level, and this splitting reduced the joint strength, despite the z-pinning resisting separation of the skin from the stiffener flange.

References

[1] Jones R, Chiu, WK and Paul J. Designing for damage tolerant bonded joints. *Composites*, Vol. 25B, pp. 201-207, 2003.

[2] Tong L, and Steven, GP. *Analysis and Design of Structural Bonded Joints*. Hingham: Kluwer Academic Publishers, 1999.

[3] Kayupov M and Dzenis YA. Stress concentrations caused by bond cracks in single-lap adhesive composite joints. *Composite Structures*, Volo. 54, pp. 215-220, 2001.

[4] Alderliesten RC. Damage tolerance of bonded aircraft structures. *International Journal of Fatigue*. Vol. 31, pp. 1024-1030, 2009.

[5] Owsley GS. The effect of z-fibre™ reinforcement on fatigue properties of stiffened composite panels, *Proceedings of the 15th Technical Conference of the American Society of Composites*, 25-27 September 2000, Texas.

[6] Rugg KL, Cox BN and Massabò R. Mixed mode delamination of polymer composite laminates reinforced through the thickness by z-fibres, *Composites*, Vol. 33, pp. 177-190, 2002.

[7] Partridge IK, Cartié DDR and Bonnington. T Manufacture and performance of z-pinned composites, *Advanced Polymeric Composites*, ed. G. Shonaike and S. Advani, CRC Press, Florida, 2003.

[8] Cartié DDR, Dell'Anno G, Poulin E and Partridge I.K., 3D reinforcement of stiffener-to-skin T-joints by z-pinning and tufting, *Engineering Fracture Mechanics*, Vol. 73, pp. 2532-2540, 2006.

[9] Lees JM and Makarov G. Mechanical/bonded joints for advanced composite structures. *Proceedings of the Institution of Civil Structures and Buildings*, Vol. 157, pp. 91-97, 2004.

[10] Chang P, Mouritz AP and Cox BN. Tensile properties and failure mechanisms of z-pinned composite lap joints, *Composites Science & Technology*, Vol. 66, pp.2163-2176, 2006.

[11] Grassi M, Cox B and Zhang X, Simulation of pin-reinforced single-lap composite joints, *Composites Science & Technology*, Vol. 66, pp.1623-1638, 2006.

[12] Byrd LW and Birman V, Effectiveness of z-pins in preventing delamination of co-cured composite joints on the example of a double cantilever test, *Composite*, Vol. 37B, pp. 365-378, 2006.

[13] Chang P, Mouritz AP and Cox BN. Elevated temperature of pinned composite laminate joints. *Journal of Composite Materials*, Vol. 42, pp. 741-769, 2008.

[14] Toral-Vazquez J, Castanie B, Barrau JJ and Didierjean S. Experimental analysis and modeling of z-pinned joints under pull-out, shear and flexure loadings, *Proceedings of the 4th International Conference on Composite Testing and Model Identification*, Ohio: 20-22 October 2008.

[15] Koh TM, Feih S and Mouritz AP. Experimental determination of the structural properties and strengthening mechanisms of z-pinned composite T-joints. *Composite Structures*, Vol. 93, pp. 2222-2230, 2011.

[16] Park Y-B, Lee B-H, Kweon J-H, Choi J-H and Choi IH, The strength of composite bonded T-joints transversely reinforced by carbon pins, *Composite Structures*, (in press).

[17] Freitas G, Magee C, Dardzinski P and Fusco T. Fibre insertion process for improved damage tolerance in aircraft laminates, *Journal of Advanced Materials*, Vol. 25, pp. 36-43, 1994.

[18] Mouritz AP, Review of z-pinned composite laminates, Composites, Vol. 31A, pp. 84-91, 2007.

[19] Childress JJ and Freitas G. Z-direction pinning of composite laminates for increased survivability, *Proceedings of the AIAA Aerospace Design Conference*, Irvine, California, February 1992, pp. 92-109.

[20] Rezai A., Cartié D, Partridge I, Irving, P, Aston T, Negre P and Langer J. Interlaminar damage resistance of z-fibre™ reinforced structural CFRP, *Proceedings of the 13th International Conference on Composite Materials*, 25-29 June 2001, Beijing.

[21] Zhang X, Hounslow L and Grassi M. Improvement of low velocity impact and compression-after-impact performance of z-fibre pinning, *Composites Science & Technology*, Vol. 66, pp. 2785-94 , 2006.

[22] Isa MD, Feih S and Mouritz AP. Compression fatigue properties of z-pinned carbon/epoxy laminates with barely visible impact damage. *Composite Structures*, Vol. 93, pp. 2269-2278, 2011.

[23] Chang P, Mouritz AP and Cox BN. Properties and failure mechanisms of z-pinned laminates in monotonic and cyclic tension, *Composites*, Vol. 37A: pp. 1501-1513 , 2006.

[24] Phillips HJ and Shenoi RA. Damage tolerance of laminated tee joints in FRP structures, *Composites*, Vol. 29, pp. 465-478, 1998.

[25] Cartié DDR, Cox BN and Fleck BN. Mechanisms of crack bridging by composite and metallic rods, *Composites*, Vol. 35A, pp. 1325-1336, 2004.

[26] Dai S-C, Dai, X, Yan W, Liu H-Y and Mai Y-W. Experimental study on z-pin bridging law by pullout test, *Composites Science & Technology*, Vol. 64, pp. 2451-2457, 2004.

[27] Yan W, Liu H-Y and Mai Y.-W. Numerical study of the mode I delamination toughness of z-pinned laminates, *Composites Science & Technology*, Vol. 63:pp. 1481-1493, 2003.

[28] Yan, W., Liu, H.-Y. and Mai, Y.-W., Mode II delamination toughness of z-pinned laminates, *Composites Science & Technology*, 2004;64:1937-1945.

[29] Birman V and Byrd LW. Effect of z-pins on fracture in composite cocured double cantilever beams, *Journal of Aerospace Engineering*, Vol. 18, pp. 51-59, 2005.

[30] Tong L. and Sun, X. Bending effect of through-thickness reinforcement rods on mode I delamination toughness of DCB specimen. I. Linearly elastic and rigid-perfectly plastic models" *International Journal of Solids & Structures*, Vol. 41, pp. 6831-6852, 2004.

[31] Koh TM, Feih S. and Mouritz AP, Strengthening mechanics of thin and thick composite T-joints reinforced with z-pins, *Composites A*, (in press).

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