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EFFECT OF METAL Z-PINS ON THE FATIGUE PERFORMANCE OF STEPPED-LAP JOINTS

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Abstract

This study aims to investigate the beneficial effects of z-pins on the structural and damage response of stepped-lap composite joints subjected to static and fatigue loading. Single stepped-lap joints were selectively reinforced within the overlap length using stainless steel z-pins arranged in different reinforcing patterns. Experimental results showed that z-pins improve both the static strength and the fatigue life of the composite joints. The damage response of unpinned and pinned samples is governed by the onset of delaminations at the joint edges and their propagation along the overlap region up to the final separation of the adherends. The pin rows closer to the edges of the joints were shown to play a major role in controlling the growth of the debonding crack. Z-pins do not delay the onset of delamination at the joint interface but reduce the delamination growth rate as soon as they start applying bridging traction forces across the delaminated area.

1. Introduction

In the past few decades, multi-layered fiber-reinforced materials have been increasingly used due to their high specific strength and stiffness, which make them the primary choice in those applications where lightweight structures result in performance improvements, energy savings, and lower operational costs. Nowadays, composite structures are progressively larger and more integrated. The need to connect sub-structures of complex geometry and different materials and, at once, ensure the load transfer between them has produced an ever-rising interest in the joining techniques. Among them, adhesive joints that keep the promise of increasing the limit load and the damage tolerance of composite joints are widely preferred. A comprehensive review of the investigations performed on adhesively bonded joints of fiber-reinforced composites can be found in [1,2].

Adhesive joints consist of two or more structural components bonded together through secondary bonding or co-curing processes without requiring machining operations (e.g., drilling and boring), thus reducing both the manufacturing costs and the probability of introducing defects in the joints. However, due to the low transverse strength of laminated composites, the high stress arising at the joint interface results in a high susceptibility to through-the-thickness damage, i.e., delamination and debonding [1]. The initiation and propagation of interlaminar cracks are a long-standing concern in designing critical load-bearing composite components. Therefore, the need to improve the fracture toughness of layered composites and composite joints has led to the development of numerous strengthening techniques, mainly based on the insertion of translaminar reinforcements [2,3], e.g., tufting, braiding, weaving, stitching, and z-pinning.

The Z-pinning approach relies upon a relatively simple manufacturing process, which consists in inserting thin fibrous or metal rods through the thickness of an uncured composite laminate. Z-pins have proven to enhance several mechanical properties of composite laminates and joints, such as the interlaminar fracture resistance, the impact and post-impact response, the ultimate strength, the damage tolerance, and the resistance to delamination [4-8]. Nonetheless, the increase in the structural properties of bonded composite joints induced by Z-pins depend on a multitude of factors, including the structural joint configuration, the pin volume fraction and diameter, the material and the surface roughness of the reinforcing pins, the location and orientation of the z-pins [6-9].

Several studies focused on the strength of stepped-lap joints under different load conditions (static tension and compression, bending, impact and fatigue loads [9-13]), but only a few attempts have been made to characterize the behavior of stepped-lap joints reinforced with Z-pins [14]. Therefore, this study analyzes the structural and damage response under tensile loads of co-cured stepped-lap composite joints reinforced through the thickness with steel Z-pins. Static and fatigue tests were carried out to characterize the effect of Z-pins on the strength of the joints and to assess their role in controlling the evolution of the damage process that leads to final failure.

2. Experimental

Composite laminates were manufactured from *HS150/ER450* (CIT, Italy) unidirectional carbon fibre/epoxy prepreg tapes (0.15 mm nominal thickness) stacked with a cross-ply layup ($[90/0]_{2s}$) to be used as adherends. Single stepped-lap joints were assembled by joining the panels along an overlap length of 40 mm without interposing any additional adhesive layer. Prior to curing, some of the joined panels were reinforced in the thickness direction with stainless steel pins obtained from a continuous wire of 0.5 mm diameter. Z-pins were manually inserted into pre-punched holes (created with a 0.5 mm needle) along straight lines parallel to the joint edges. After pin insertion, the protruding wires were sheared off employing a sharp cutter.

Three different densities and patterns of pinning reinforcement were used to reinforce the overlap of the joint panels. In particular, joint panels with 2, 3, and 4 rows of pins were manufactured with the Z-pinning patterns detailed in fig. 1. Both unpinned and pinned joint panels were cured in an autoclave at a pressure of 3 bar and a maximum temperature of 125°C. 20 mm wide coupon samples were finally cut from the consolidated panels with the dimensions shown in fig. 2.

The samples were tested under static and fatigue tensile loading at room temperature. The static tests were performed using a *250 kN Instron* servo-electric testing machine operated in displacement control with a crosshead rate of 1 mm/min. The fatigue tests were conducted using a *10 kN Instron* electrodynamic testing machine operated in load control to apply a sinusoidal waveform with a load ratio R of 0.1 and a frequency of 10 Hz. During testing, the load, the crosshead displacement, and the longitudinal strain were continuously recorded to monitor the change in sample stiffness with fatigue damage evolution. The strain was measured by an extensometer with a 62.5 mm gauge length mounted across the overlap region of the joint.

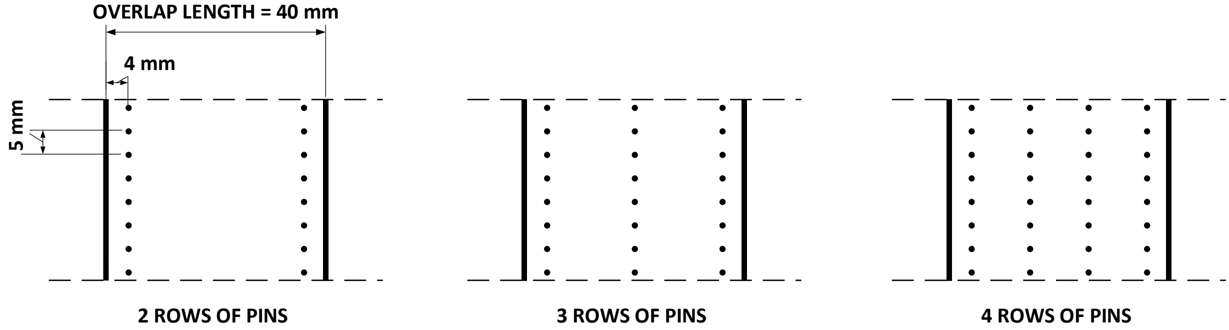


Figure 1. Z-pinning patterns in the overlap region of the joint

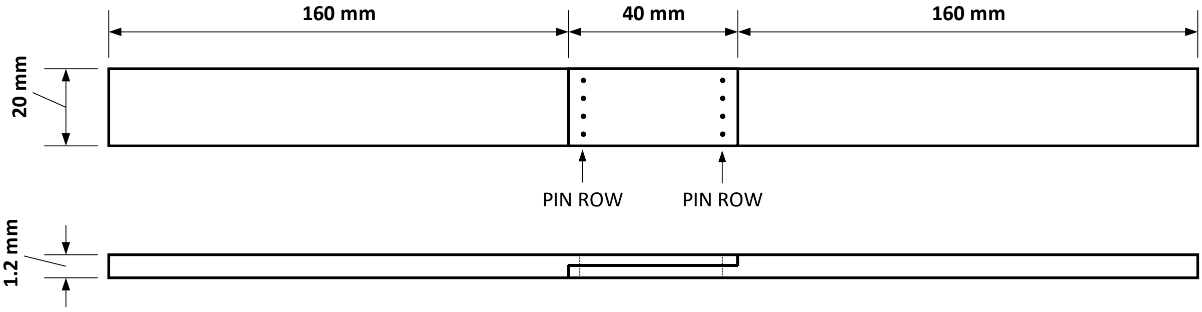
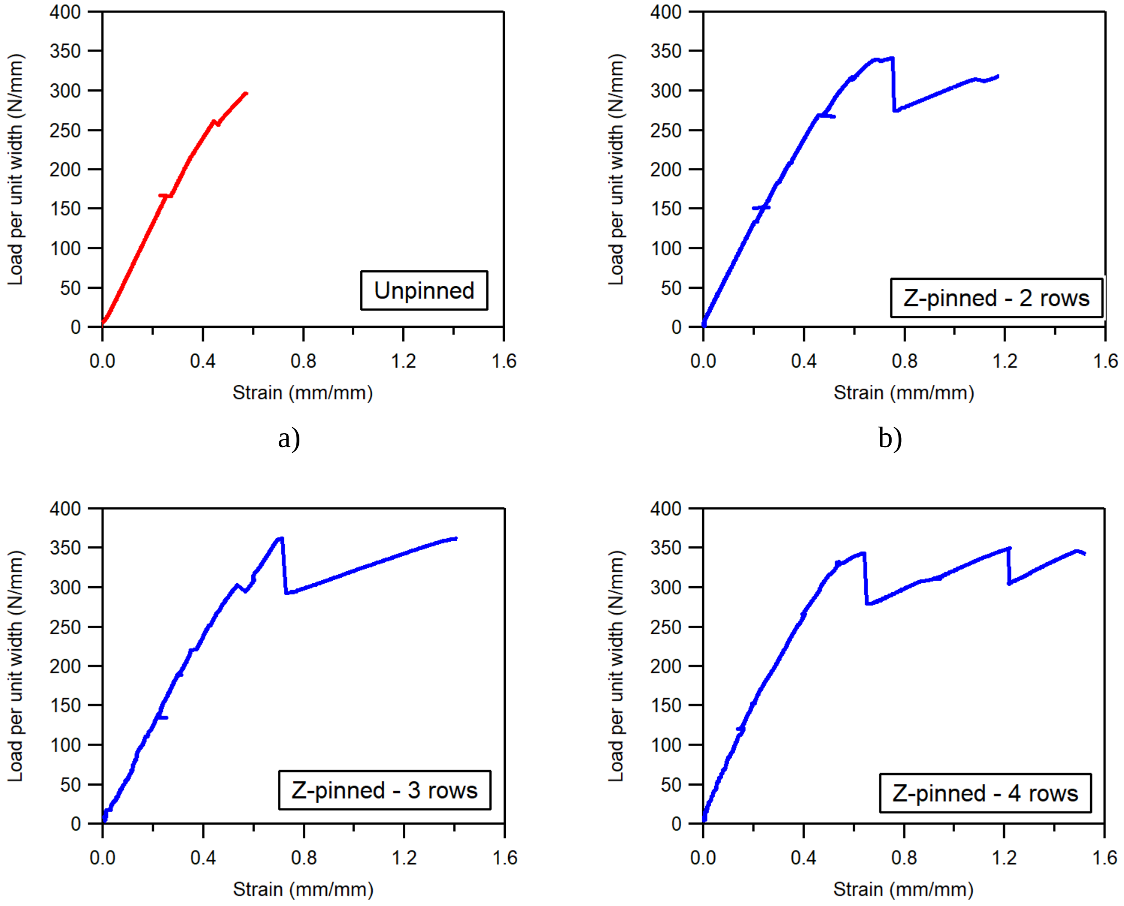


Figure 2. Geometry of joint samples (dimensions not to scale)

3. Results and discussion

Fig. 3 shows the load (per unit width) – strain curves of unpinned and Z-pinned samples subjected to static loading. The curves of unpinned joints show an essentially brittle failure with a generally linear trend up to complete joint separation. The sudden strain irregularities visible in the graph correspond to the onset of small cracks in the resin-rich regions at the edges of the overlap (fig. 4). These cracks trigger the onset of small delaminations at the joint interface (fig. 4), which are responsible for the nonlinear behaviour exhibited by the unpinned samples just before the final separation of the adherends. The ultimate failure occurs suddenly due to the unstable propagation of these delaminations over the entire joint interface when the load reaches a critical value.

The failure of Z-pinned joints is governed by the same sequence of failure events observed in unpinned joints. However, the load-strain curves of fig. 3b, c, and d reveal that the final separation of the Z-pinned joints is preceded by a more progressive fracture process, during which the growth of the interfacial crack proceeds in steps, owing to the restraining effect of through-thickness pins, which reduce the energy available at the front of the crack and thus arrest or delay its propagation. The traces of fig. 3 show that the introduction of Z-pins not only improves the strength of the joints, but also makes them capable of sustaining high loads over much larger strain ranges. A comparison of the initial stiffness and the strength values of unpinned and Z-pinned joints, presented in fig. 5, shows that the presence of Z-pins does not affect the stiffness of the joints but increases their tensile strength by about 15%. It is worth noting that the increase in strength achieved by Z-pinning does not appear to be affected by the density and the number of rows of the through-thickness reinforcement. This evidence indicates that the pin rows closer to the edges play a major role in delaying the unstable propagation of the debonding crack at the joining interface, while no evident beneficial effect is provided to the load capacity of the joint by the more internal pin rows. This also suggests that the debonding crack becomes unstable before reaching the internal rows of pins and, thus, prior to activating their potential bridging tractions.



a) b) c) d)

Figure 3. Static tensile load-strain curves of unpinned (a) and Z-pinned (a,b,c) joints

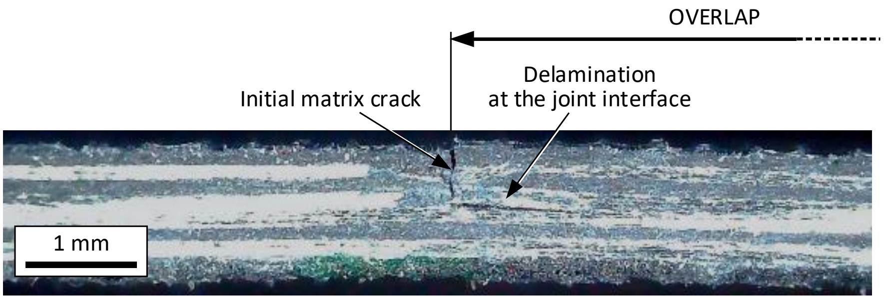
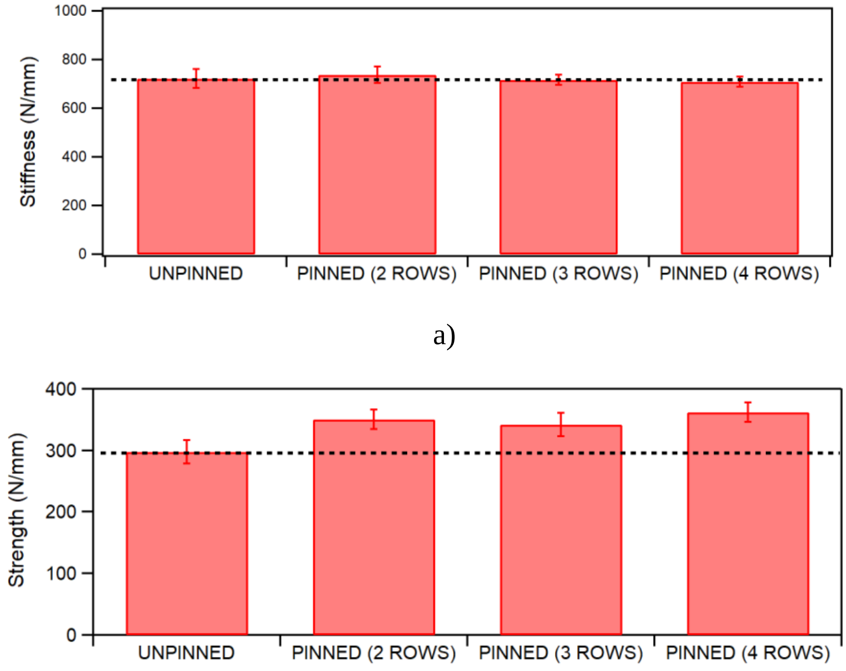


Figure 4. Initial matrix crack and delamination at the edge of the joint overlap



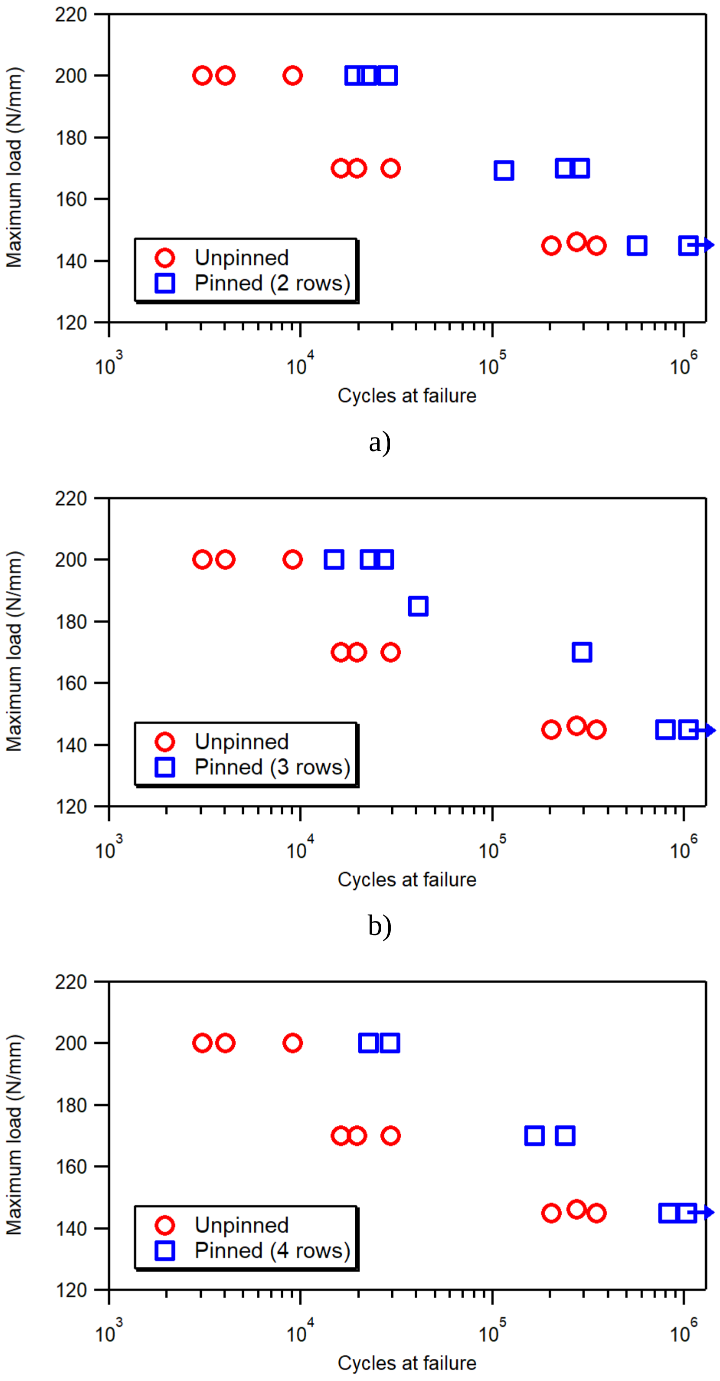
a)

b)

Figure 5. Initial stiffness (a) and tensile strength (b) of unpinned and Z-pinned joints

The fatigue responses of unpinned and Z-pinned joints are illustrated in the S-N graph of fig. 6, where the maximum applied load per unit width is plotted as a function of the number of cycles to failure. The data show that the three considered Z-pinning configurations significantly improve the fatigue strength of the joints. The progression of the damage mechanisms leading to the ultimate fatigue failure is the same observed under static load: the initial cracks that occur during the first fatigue cycle at the resin-rich discontinuities between the ends of the adherends trigger the development of delaminations at the joint interface. The delaminations then grow steadily with fatigue cycling until they become critical, propagating quickly across the entire overlap of the joint and resulting in the ultimate failure of the sample. However, while in unpinned laminates the delamination may propagate unrestrained along the overlap length, in Z-pinned joints the delamination growth is drastically slowed down as soon as the front of the debonding crack grow beyond the first row of pins; at this stage the pins become able to bridge the delaminated surfaces and reduce the stress intensity at the crack front. It may be noted that, similarly to what observed in static tests, the addition of one or two internal rows of pins do not appear to provide any evident improvement in the fatigue performance of the joints.

The reduction of the delamination growth rate achieved by Z-pinning is evident by comparing the decay of stiffness as a function of fatigue cycles in unpinned and Z-pinned samples. Typical histories of stiffness degradation are shown in the graphs of fig. 7, which plot the stiffness (normalized to the stiffness measured during the first fatigue cycle) versus the number of cycles for unpinned and 2-row Z-pinned joints subjected to the same maximum load (170 N/mm). We see that unpinned and z-pinned joints exhibit a similar rate of stiffness decrease in the initial stage of the fatigue life (i.e., when the delamination cracks are not long enough to reach the first row of pins and thus exploit their potential toughening mechanism). The rate of stiffness decrease of the Z-pinned joint becomes, however, much lower than that of the unpinned joint in the following stage of the fatigue life, when the delamination crack has grown to a length sufficient for Z-pins to start applying traction loads across the delaminated surfaces.



a)

b)

c)

Figure 6. Comparison of S-N fatigue data of unpinned and 2-row (a), 3-row (b) and 4-row (c) Z-pinned joints.

The distance between the edge of the overlap and the adjacent row of pins appears, therefore, a key factor in the fatigue behaviour of Z-pinned joints. In order to explore this aspect, several joints were manufactured with z-pinning patterns analogous to those illustrated in fig. 1, but with a distance between the edges of the overlap and the adjacent rows of pins increased to 10 mm from the original value of 4 mm. The S-N data reported in fig. 8 show that this class of joints provide performances significantly worse than those of the base Z-pinned joints and comparable, or only slightly better, than those of unpinned joints. These results indicate the importance of inserting the pins close to the edges of the joints to activate the bridging action of Z-pins since the early stages of crack propagation and exploit their beneficial role for a large fraction of the fatigue life.

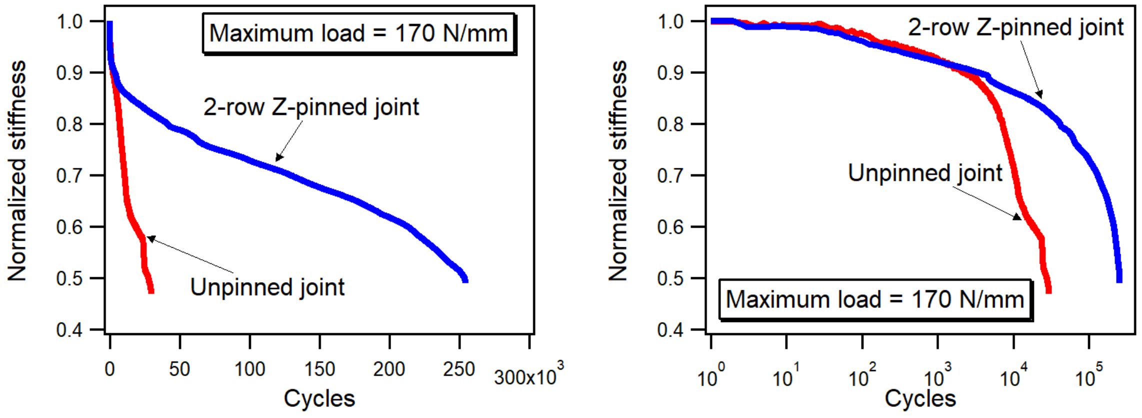


Figure 7. Degradation of the normalized stiffness of unpinned and Z-pinned (2-pin rows) joints fatigued at a maximum load of 170 N/mm. The numbers of cyles are plotted on a linear scale in the left graph and on a logarithmic scale on the right graph.

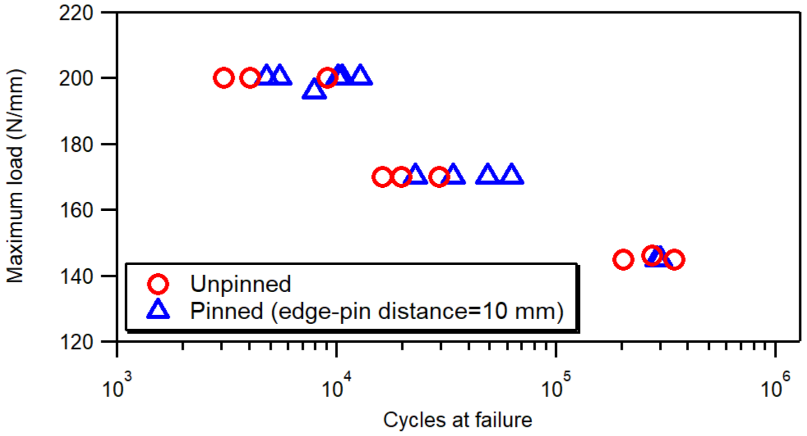


Figure 8. S-N fatigue data of unpinned and Z-pinned joints with a 10 mm distance between the overlap edge and the adjacent row of pins

4. Conclusions

This study examined the static and fatigue tensile behaviour of carbon/epoxy stepped-lap joints reinforced by steel Z-pins in the overlap region. Joints with 2, 3 or 4 rows of pins were manufactured to investigate the performance improvements achievable through different patterns of through-thickness reinforcement. The main findings of the study can be summarized as follows:

- For both unpinned and Z-pinned joints, the damage process that leads to ultimate failure starts with small matrix cracks at the resin-rich gaps between the ends of the adherends. The cracks promote the development of delaminations, which grow at the joint interface up to complete separation of the adherends.
- Z-pinning increases the static strength of the joints and enhances their damage tolerance, by allowing the joints to provide a significant load-carrying capacity over much larger strain ranges than those of the unpinned counterparts. The improvement in the static strength achieved by Z-pinning (about 15%) is substantially independent of the pinning configuration (2, 3 or 4 rows).
- The fatigue life of the joints is improved by all Z-pinning configurations. The increase in fatigue life exhibited by the pinned joints is due to reduced crack growth rate generated by the bridging action of the pins. No remarkable differences were observed between the fatigue performances of the joints reinforced with 2, 3 or 4 pin rows.
- The Z-pins adjacent to the overlap edges were found to play the primary role in controlling the static and fatigue behaviour of the Z-pinned joints.

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