Journal of
Composites Science

Article

Effect of Selective Z-Pinning on the Static and Fatigue Strength of Step Joints between Composite Adherends

Gabriela Loi *, Pasquale Buonadonna , Rayane El Mohtadi , Mauro Carta , Daniele Lai, Mohamad El Mehtedi and Francesco Aymerich *

Department of Mechanical, Chemical and Materials Engineering, University of Cagliari, 09123 Cagliari, Italy
* Correspondence: gabriela.loi@unica.it (G.L.); francesco.aymerich@dimcm.unica.it (F.A.)

Abstract: The z-pinning reinforcement technique, which involves inserting thin pins through the body of a laminate, has proven highly effective in enhancing the strength of various composite joint configurations. This investigation aims to explore the enhancements achievable through selective z-pinning at very low pin contents on both the static and fatigue performance of composite joints. Single-step joints between carbon/epoxy adherends were reinforced using steel pins arranged in two, three, or four rows of pins parallel to the edges of the overlap, resulting in pin contents ranging from 0.2% to 0.4%. Joint panels were manufactured through co-curing, and coupons were extracted from the panels for static and fatigue tensile testing. The experimental tests show that z-pinning improves the static strength (by about 15%) and extends the fatigue lives of the joints. The ultimate failure of both unpinned and pinned joints is due to the unstable propagation of a crack at the bond line. The superior performances of pinned joints are mainly due to the bridging tractions imposed between the crack faces by z-pins, which delay the growth of the debonding crack. The enhancements in static and fatigue strength achieved by z-pinning were essentially independent of the number of pin rows, and the pins positioned near the joint edges were found to play a dominant role in controlling the structural performance of pinned joints.

Keywords: z-pinning; step joints; fatigue; delamination

Citation: Loi, G.; Buonadonna, P.; El Mohtadi, R.; Carta, M.; Lai, D.; El Mehtedi, M.; Aymerich, F. Effect of Selective Z-Pinning on the Static and Fatigue Strength of Step Joints between Composite Adherends. *J. Compos. Sci.* **2024**, *8*, 84. https://doi.org/10.3390/jcs8030084

Academic Editor: Francesco Tornabene

Received: 30 December 2023
Revised: 21 January 2024
Accepted: 19 February 2024
Published: 24 February 2024

1. Introduction

Multi-layered fiber-reinforced materials have seen increasing use in the past few decades due to their high specific strength and stiffness. These qualities position them as the primary choice in application fields where lightweight structures lead to performance improvements, energy savings, and lower operational costs. The progressive increase in the size of composite structures and the consequent need for the integration of different structural elements has generated a growing interest in joining configurations capable of enhancing the load-bearing capacity and reliability of joints under static or fatigue loads.

Adhesive joining is generally the preferred method for joining thin composite adherends because, compared to mechanical fastening, bonded or co-cured joints eliminate stress peaks and bearing loads caused by bolts or rivets, maintain the integrity of the fibers, and ensure a more uniform stress distribution over the joined area [1–3]. Furthermore, bonded joints typically exhibit a lower weight than mechanically fastened joints and enable the design of smooth external surfaces. Bonded joints, however, exhibit a high susceptibility to debonding and delamination damage due to the high peeling and shear stresses arising at the ends of the joining interface, as well as the low through-thickness strength of laminated composites [4–6]. The initiation and growth of debonding cracks at the joining surface and delaminations at interfaces within the adherends are, therefore, among the main damage modes that lead to the ultimate failure of bonded composite joints.

Derived from these basic observations, several techniques have been suggested to improve the strength of bonded or co-cured composite joints [5,7]. As an example, these techniques include the adoption of wavy or reverse-bent joint configurations [8,9], the optimization of the geometries of the terminations of the adherends [10,11], and the increase in the number of joining interfaces [7,12]. Another strategy involves introducing translaminar reinforcement across the thickness of the joint, using either continuous threads (stitching) or carbon or metal pins (z-pinning) [13–22]. Z-pinning, in particular, has demonstrated its effectiveness in improving the tensile strength of various configurations of lap joints between composite adherends [23–26].

As an example, Mouritz and coworkers [14] achieved significant enhancements in both the tensile strength and elongation limits of single-lap carbon/epoxy joints by inserting carbon z-pins (0.28 mm in diameter) over the entire overlapping region (30 mm). The enhancement in the load-carrying properties and the failure modes of the reinforced joints were observed to be dependent on z-pin content. The strength of the pinned joints increased by 8% and 41% with the introduction of 0.28 mm diameter pins at densities of 0.5% and 2%, respectively. However, the increase in ultimate strength dropped to 23% when the pinning density was further increased to 4%. The improvement in the load-carrying capacity of the joints was attributed to the toughening role of pins, which, by transferring loads across the bond line, delayed (for the 0.5% pin density) or even arrested (for the 2% and 4% pin densities) debonding growth at the joint interface. In joints with the lowest pin density (0.5%), the ultimate failure occurred due to the unstable propagation of the bond-line crack followed by the shear failure of pins. Conversely, in joints with higher pin densities (2% and 4%), the delamination was arrested because of the bridging action of the z-pins, and the collapse of the joint occurred due to the failure of one of the adherends at the row of pins close to the edge of the overlap. The effect of z-pins on the damage tolerance of the joints was also investigated in [17] by comparing the strength of unreinforced and pinned joints containing artificial debonding cracks with lengths ranging between 5% and 70% of the overlap. It was consistently observed that the presence of z-pins increased the damage tolerance of joints across all the examined pre-existing crack lengths, enabling strength improvements between 30% and 50%. Significant improvements in strength (20%) and especially elongation limits (250%) were also recently observed in single-step joints after reinforcing the overlapping region with steel pins at a 2% density [22]. The efficacy of z-pins was, however, seen to decrease with an increasing number of interfaces and no improvements in strain and elongation were achieved with z-pinning for multi-step joints with six bonding interfaces.

The specific mechanisms of damage and deformation generated under load using through-thickness rods or pins across composite adherends have been experimentally observed and discussed in [27–29]. The damage modes evolve through a sequence of main stages that include debonding of rods from the laminate, with the subsequent pull-out resisted to by interfacial friction forces; axial and shear deformation of the rods; lateral deflection into the laminate (ploughing) with an ensuing enhancement of friction (snubbing); and ultimate failure due to either a complete pull-out or shear rupture of the rod. The relative importance of the contribution of different mechanisms to the debonding resistance of the composite depends, however, on several factors, which include the content, diameter, length, orientation, and material of the pins, the layup, and curing parameters of the laminate, the degree of mode-mixity, the environmental conditions, etc. [18,25,30].

Choi and coworkers presented in [19,20] experimental results on the response to tensile loads of pinned single-lap joints between quasi-isotropic carbon/epoxy adherends. The joints were reinforced with 0.5 mm steel z-pins, uniformly distributed over the overlap region at an areal density of 2%. The tests, conducted under different temperature and humidity conditions, showed that z-pinning enhanced the static strength of the joint by approximately 15% across all examined environmental conditions. Larger improvements in strength were achieved using pins featuring a jagged surface profile, which ensured better adhesion of the pins to the embedding resin.

The performances of lap joints reinforced using a different hybrid technology, wherein a thin metal sheet with protruding spiked pins is inserted between the two prepreg adherends before consolidation, were examined in a series of studies [31–36]. As an example, the effect of metal inserts featuring three distinct patterns of steel pins (with pins uniformly distributed over the overlap region, concentrated near the overlap edges, or clustered at the overlap corners) on the strength of single-lap carbon/epoxy adherends was investigated in [35]. The total cross-sectional area of pins was approximately 1.6% of the joining area for all three pinning patterns. The strength of joints with pins distributed across the entire overlapping region was found to be comparable to that of the reference unpinned joints. The strengths of joints with pins primarily positioned near the edges or corners of the overlap area were even lower than those of the unpinned samples. Nevertheless, all pinned joints exhibited failure strains significantly higher than those of their unpinned counterparts. Post-mortem analyses revealed a transition in the failure mode of the joints, which changed from pin shear rupture when the pins were uniformly distributed over the bond region to being controlled by pin pull-out when they were clustered at the overlap corners. The static strength properties of carbon/epoxy lap joints reinforced by metal sheets with spiked pins arranged in various patterns and densities were also examined in [32]. The load-carrying capacity of the joints was increased by 11% to 55% depending on the pinning pattern and content. It was observed that increases in pin content generally led to increases in joint strength, although the extent of the improvements depended on the layout of the pins.

Very few experimental investigations have been specifically carried out on the fatigue response of lap joints reinforced by z-pins [14,19,20] or through spiked inserts [31,33–36]. The results of the test reported in [14], conducted on lap joints reinforced with 0.28 mm carbon pins at areal densities of 0.5%, 2%, or 4%, show that the crack-bridging mechanisms applied by the pins significantly extend the fatigue life of the joints. Consistent with the behavior under static loads, the joints exhibited the best fatigue performance at an intermediate pin content (2%), with the failure mode shifting from bond-line cracking at the lowest pin content (0.5%) to adherend rupture as the pin content was increased to the highest value (4%).

The fatigue performances of unpinned and pinned carbon/epoxy lap joints were compared in [19,20] under different environmental conditions. The joints were reinforced with metal pins distributed across the entire overlap region at a 2% areal density. At ambient temperature and humidity conditions, the fatigue strengths at 10^6 cycles of the reference joints were found to increase by 10% after pinning. Further improvements in fatigue strength could be achieved using pins with a jagged surface. Additionally, the presence of z-pins was observed to mitigate the degradation of the fatigue strength induced by more severe temperature and moisture conditions.

The results of fatigue testing on single-lap joints reinforced with spiked metal sheets are reported in [31,33,34]. Despite significant variability, preliminary testing on joints with spiked inserts positioned at the edges of the overlap [31] revealed longer fatigue lives for reinforced joints compared to their unreinforced counterparts. In contrast, the fatigue lives of lap joints reinforced over the entire overlap region with 0.6%, 1.2%, and 1.4% content of spikes were found to be comparable to or even lower than those of unreinforced joints [33]. Spiked sheets made of different materials (steel and titanium), featuring various spike geometries, and manufactured using different technologies (cold metal welding or press fitting), were used in [35] to reinforce carbon/epoxy lap joints for fatigue tests. The protruding spikes, ranging in diameter from 0.76 to 1.2 mm, were arranged in rows positioned close to the edges of the overlap. It was observed that the fatigue performance of the spike-reinforced joints varied—being worse, comparable, or better than that of the reference joints—depending on the specific material and the type of spiked insert used to connect the two adherends.

Because of the limited amount of experimental data and the somewhat conflicting findings of previous studies, there is a clear need for further investigation into the role of z-pins in enhancing the load-carrying capacity and reliability of fatigued joints. In this respect, it is worth noting that most of the reinforcing patterns used in the above-mentioned studies involve comprehensive pinning across the entire overlap region, typically with a relatively high pin density (mostly ranging between 1% and 4% in volume). The potential enhancements achievable by utilizing pins in specific joint regions and at significantly lower contents remain, however, to be further explored. To this end, this study examines the effect of selective z-pinning on the strength properties under both static and fatigue tensile loads of step joints between carbon/epoxy adherends. The first type of joint was manufactured by inserting a row of z-pins at each of the overlap edges, resulting in an areal density of 0.2%. Two further joint types, with one or two extra rows of pins positioned toward the overlap center, were prepared, and examined for comparative analyses. The experimental observations focused particularly on characterizing the role of z-pins and assessing the impact of their position within the joining area on the structural performance and damage response of the joints.

2. Materials and Methods

Single-step joints were manufactured by joining cross-ply $[90/0]_{2s}$ adherends consisting of unidirectional carbon fiber/epoxy prepreg layers (*HS150/ER450*; CIT, Legnano (Italy)). The adherends were joined over an overlap length of 40 mm at a 0°/0° interface without the use of any additional adhesive layer. Before curing, some of the joined panels were reinforced in the thickness direction using steel (*ASTM A401*) pins obtained from a continuous wire of 0.5 mm diameter. Z-pins were manually inserted into pre-punched holes (made with a 0.5 mm needle) along straight lines parallel to the joint edges. Following pin insertion, the protruding wires were sheared off through employing a sharp cutter. Three different pinning patterns were chosen to reinforce the overlap of the joint panels, as shown in Figure 1. In the first type of joint (2-row pinned joints), the z-pins were inserted along rows at a distance of 4 mm from the overlap edges (Figure 1a); for the second (3-row pinned joints, Figure 1b) and third type (4-row pinned joints, Figure 1c) of pinned joints, one or two additional rows of pins were, respectively, inserted at uniform distances from the two pin rows near the overlap edges. The spacing between adjacent pins along any row was maintained at a constant 5 mm. The resulting areal densities of pins over the joining area are in the order of 0.2%, 0.3%, and 0.4% for the three joint types. After z-pinning, the joint panels were vacuum-bagged and consolidated in an autoclave for 2 h under a pressure of 3 bar and at a maximum temperature of 125 °C. It is known [25] that the force applied when cutting the pins protruding from the panel and the pressure applied during consolidation introduce, especially for thin adherends, a misalignment of the pins with respect to the thickness direction. An average offset angle of approximately 25°, consistent with similar values reported in [37,38] for 0.5 mm carbon pins, was measured from a series of micrographs obtained from polished sections extracted from the cured panels.

Identical panels without reinforcing pins, intended for use as reference material, were also fabricated and cured under the same conditions as the pinned panels. Coupon samples with an average thickness of 1.2 mm and the dimensions shown in Figure 2 were finally cut from the consolidated panels for static and fatigue testing.

The static tests were performed using a 250 kN Instron servo-electric testing machine operating 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 and the longitudinal strain were continuously recorded to monitor the change in sample stiffness with fatigue damage evolution. The strain was measured using an extensometer with a 62.5 mm gauge length mounted across the overlap region of the joint.

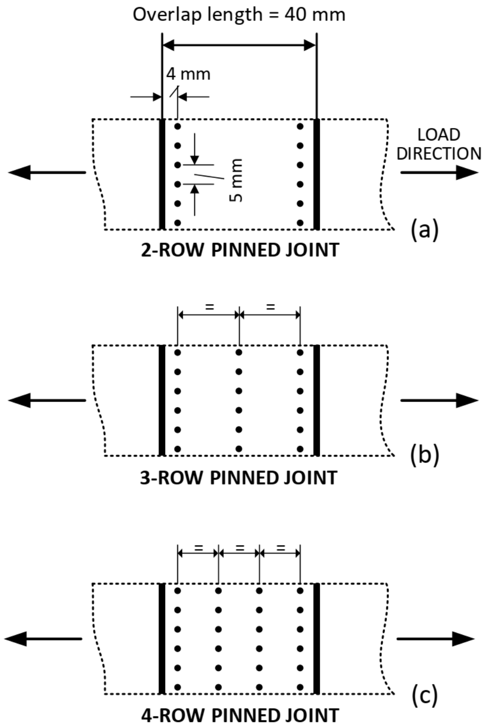

Figure 1. Z-pinning patterns of the three types of pinned joints: (**a**) 2-rows pinned joint, (**b**) 3-rows pinned joint, and (**c**) 4-rows pinned joint.

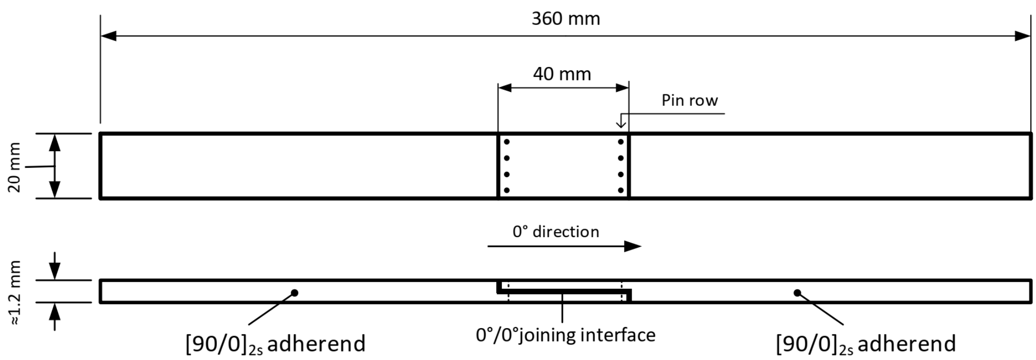

Figure 2. Geometry of coupon samples for static and fatigue tests (dimensions not to scale). The figure displays a 2-row pinned-joint configuration.

3. Results and Discussion

3.1. Static Tests

Figure 3 shows the typical load (per unit width) vs. strain curves of unpinned and z-pinned joints subjected to tensile static loading, while their static strengths are compared in Figure 4. Unpinned joints exhibit an almost linear behavior across most of the strain range, and ultimate failure occurs through an essentially brittle fracture. Damage initiates in the form of cracks in the resin regions at the terminations of the adherends (Figure 5a). The onset of these cracks is signaled by noise, as well as by the small, sudden strain jumps that are visible in the linear stage of the stress–strain curves. With increasing loads, the cracks trigger the development of small delaminations at the joint interface (Figure 5b), which are responsible for the nonlinearity observed in the load–strain curve just before ultimate failure. When the load reaches a critical value, the delaminations propagate unstably across the entire joint interface, resulting in the sudden complete separation of the two adherends. Direct observations of the joint sides during the tests revealed that small bond-line delaminations initially form at both edges of the overlap; as the load increases, however, one of these delamination cracks begins to grow larger, ultimately controlling the final failure of the joints.

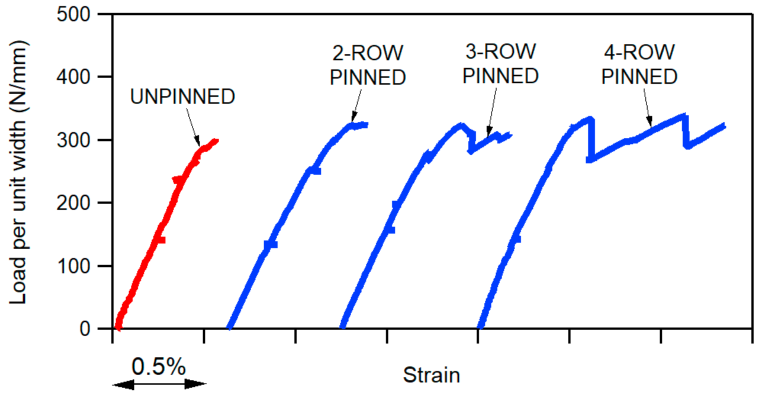

Figure 3. Load vs. strain curves of unpinned and z-pinned joints under static load. The curves have been shifted for clarity.

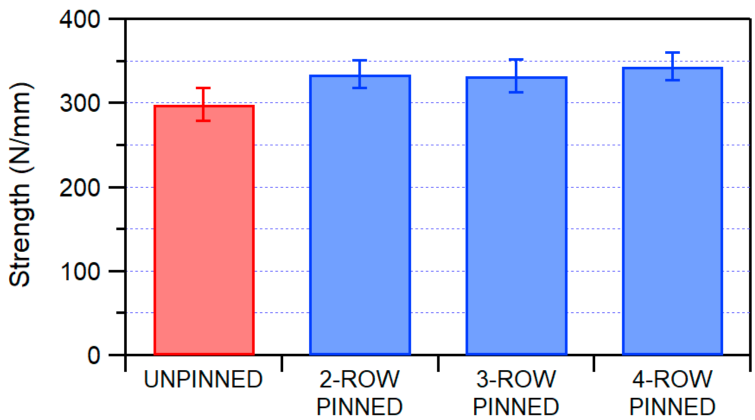

Figure 4. Static strengths (maximum load per unit width) of unpinned and z-pinned joints. The error bars indicate one standard deviation.

As seen in Figures 3 and 4, z-pinned joints exhibit an approximately 15% higher strength and, especially for joints reinforced with three of four pin rows, retain their load-carrying capacity over a wider strain range than unpinned joints. The sequence of the damage events occurring in z-pinned joints is similar to that observed in unpinned joints, wherein cracks initially form at the resin regions between the ends of the adherends and subsequently branch out as delamination cracks at the joining interface. However, the ultimate failure of pinned joints is preceded by a more progressive fracture process, during which the joints may sustain significant loads over relatively large strains. The examination of the fractured surfaces at the joint interface shows that z-pins typically pull out from one of the two adherends after debonding from the embedding laminate (Figure 6), while no broken or plastically deformed z-pins could be observed. Two characteristic damage mechanisms induced by the presence of the pins were identified on the fracture surfaces. The first mechanism involves crushing damage occurring in the resin-rich region surrounding the pins as they plough through the laminate while transferring the shear load between the adherends (Figure 7a). Directly associated with this damage mode, the second mechanism consists of long and narrow delaminations that develop at the 0°/90° interface of the continuous adherend adjacent to the joining interface (Figure 7b). These delaminated strips originate from the regions damaged by the penetrating action of the pins and grow along the 0° direction, with a width approximately equal to the pin diameter. A similar damage form was also observed in [21] on pinned CLS (Cracked Lap Shear) specimens.

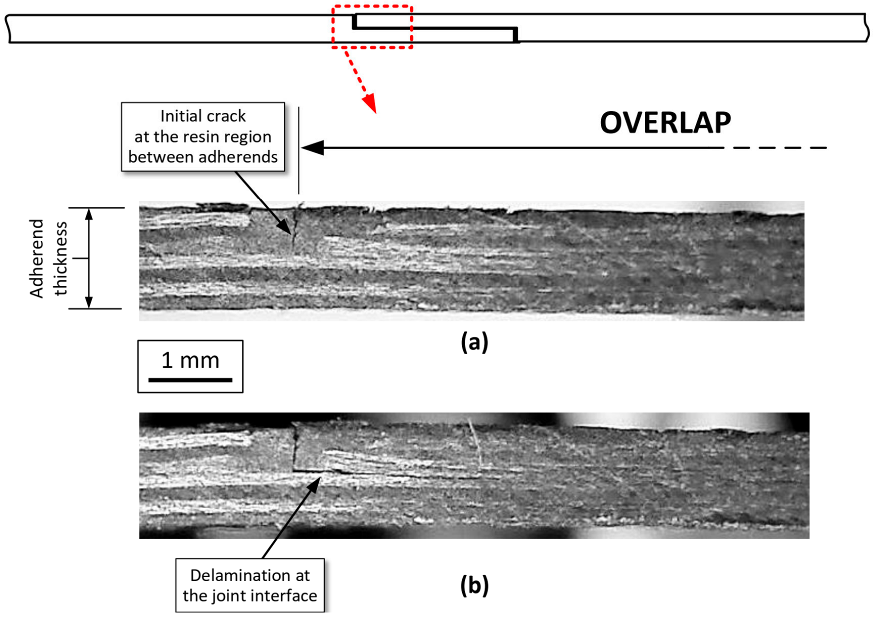

Figure 5. Initial crack in the resin region at the end of the adherends (**a**) and delamination crack at the joint interface (**b**).

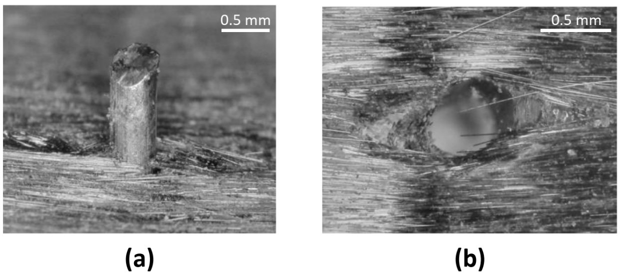

Figure 6. Pin pulled out after debonding from one adherend (**a**) and corresponding hole on the other adherend (**b**).

The increased strength of pinned joints is due to the bridging effect of through-thickness pins, which reduce the energy available at the front of the delamination cracks, thereby delaying their propagation. The energy absorptions associated with the debonding and pullout of the pins from the laminate, as well as with the crushing and delamination damage induced by the ploughing action of pins, also contribute to enhancing the capacity of pinned joints to withstand high loads in the presence of significant debonding at the joint interface.

It is important to note that the amount of strength increase achieved by z-pinning does not change with the number of pin rows (see Figure 4). This evidence indicates that the pins closer to the edges play the most dominant role in controlling the strength performance of the pinned joints. The addition of one or two internal rows of pins does indeed further hinder and postpone the catastrophic propagation of the bond-line delamination, as indicated by the higher strain to failure (Figure 3), but it does not yield any beneficial effect on the maximum load-carrying capacity of the joints.

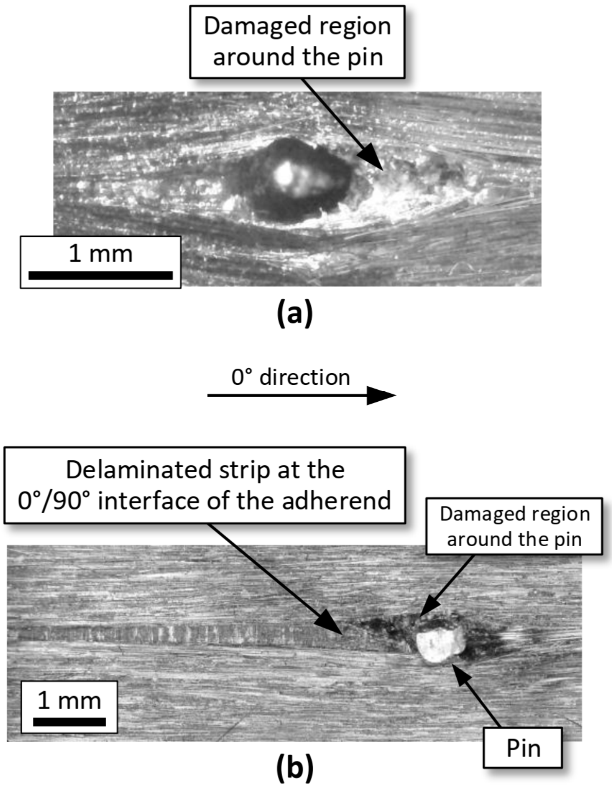

Figure 7. Damage in the resin region surrounding the pin (**a**) and delaminated strip at the 0°/90° interface of the continuous adherend adjacent to the joining interface (**b**).

3.2. Fatigue Tests

The effect of z-pinning on the fatigue performance of the joints is shown in the fatigue life graphs of Figure 8, which plot the maximum applied load per unit width against the number of cycles at failure. The continuous lines in the graphs represent the best-fit (least-squares) linear traces through the experimental fatigue data. The graphs of Figure 8 show that the fatigue lives of all z-pinned joints are significantly longer than those of the unpinned joints. Furthermore, when comparing the fatigue data from all three types of pinned joints in the same graph (Figure 9), it becomes evident that the insertion of the additional internal rows of pins does not result in any noticeable improvement in the joints' fatigue performance. These results are analogous to those obtained under static loading and clearly indicate that the rows of z-pins closer to the overlap edges play the dominant role in improving the structural performance of the joint under both static and fatigue loads.

The graphs in Figure 8 also show that the fatigue curves of unpinned and pinned joints exhibit similar slopes, suggesting that the introduction of z-pins does not significantly alter the damage modes that lead to fatigue failure in unpinned joints [39,40]. Moreover, when the fatigue stress values of the different types of joints are normalized by dividing them by their respective static strength, all fatigue data nearly converge into a single curve (Figure 10). This convergence suggests that the enhancement in fatigue performance resulting from z-pinning is governed by the same toughening mechanisms that improve static strength.

Direct inspections indeed confirmed that the sequence of damage modes that characterize the fatigue response of unpinned and pinned joints is analogous to that previously described for static loads. In both unpinned and z-pinned joints, matrix cracks initiate in the resin regions at the ends of the overlap, subsequently growing as delamination cracks at the bond line between the adherends. These delaminations steadily propagate with increasing fatigue cycles until the dominant delamination reaches instability, resulting in complete bond line delamination and final joint failure. Post-mortem examinations of the unpinned joints reveal relatively smooth fracture surfaces at the joint overlap. Conversely, the fracture surfaces of the pinned joints exhibit a more irregular pattern, with intact pins protruding from one adherend and corresponding cavities left by the debonded pins on the other adherend, as previously described for static tests (see Figure 6). The damage resulting from the ploughing of shear-loaded pins into the surrounding resin still promotes the development of long, narrow delaminated strips that extend along most of the joint length (compare Figure 7). None of the pin-reinforced fatigued joints showed any broken or permanently deformed pins.

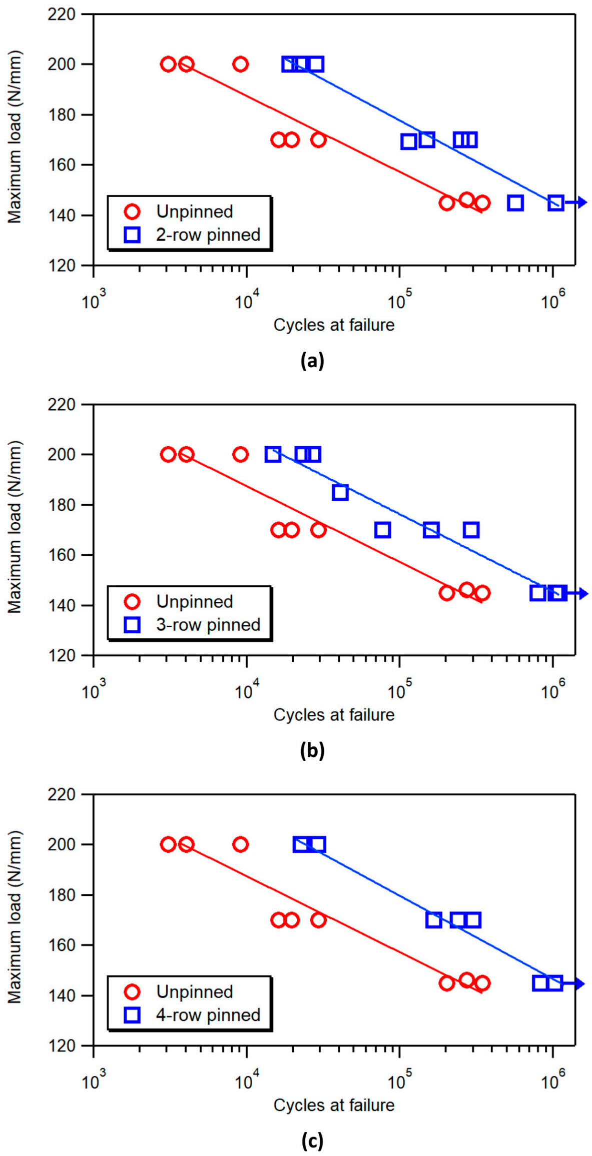

Figure 8. Fatigue life curves of unpinned (reference) and 2-row (**a**), 3-row (**b**), and 4-row (**c**) pinned joints. Arrows indicate run-out tests.

The experimental observations carried out during the fatigue tests consistently show that in both unpinned and pinned laminates the delamination between the adherends propagates unrestrained from the edge of the overlap until the debonding crack extends beyond the first row of pins. At this stage, the pins start bridging the delaminated surfaces, mitigating the stress intensity at the crack front, and thus delaying crack growth. The reduction in the delamination growth rate resulting from the presence of z-pins becomes evident when comparing the stiffness decay due to fatigue cycling between unpinned and pinned samples. As an example, typical histories of stiffness degradation are shown in the graphs of Figure 11, which report the normalized stiffness versus the number of cycles for unpinned and 2-row pinned joints subjected to the same maximum loads. The normalized stiffness reported in the graphs was determined by dividing the stiffness measured at the current cycle by the stiffness recorded during the first fatigue cycle. Similar histories were measured for joints reinforced with 3 or 4 rows of pins. We see that unpinned and z-pinned joints exhibit a comparable rate of stiffness decrease in the initial stage of the fatigue life, during which the delamination cracks are not long enough to reach the edge rows of pins and thus exploit their potential toughening mechanism. The rate of stiffness decrease in the pinned joint becomes, however, much lower than that of the unpinned joint in the subsequent stage of the fatigue life, when the delamination crack has grown to a sufficient length for z-pins to start applying their bridging tractions across the bond-line crack. The beneficial role of the edge rows of z-pins is even more evident when comparing the trends in the growth of the major delamination crack with fatigue cycles between unpinned and pinned joints. An example is shown in the graph of Figure 12, which plots the lengths of the dominant debonding crack measured at specific fatigue cycles in unpinned and pinned joints subjected to a maximum load of 200 N/mm. The data show that the rate of crack growth of the pinned joint reduces significantly as soon as the debonding crack extends beyond the row of pins at 4 mm from the overlap edge.

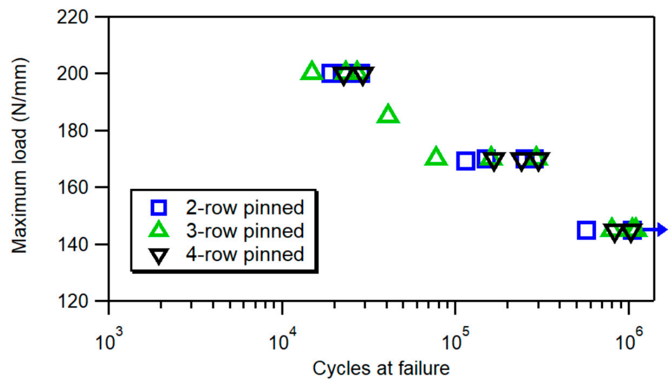

Figure 9. Fatigue life data of 2-row, 3-row, and 4-row pinned joints. Arrows indicate run-out tests.

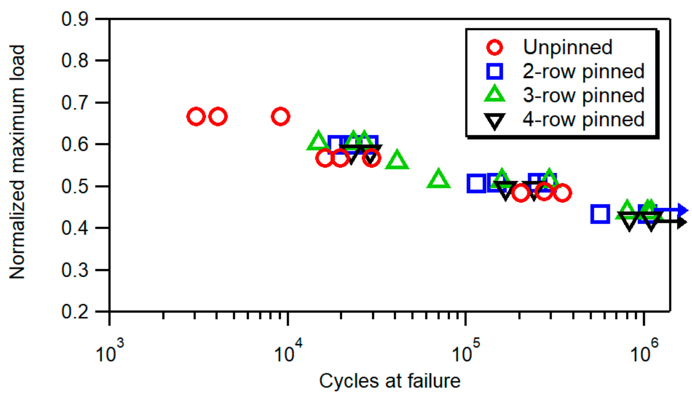

Figure 10. Fatigue strength data of unpinned and pinned joints normalized to their respective static strength. Arrows indicate run-out tests.

As described earlier, the experimental results indicate that the enhancement in the structural behavior of the joints generated using the examined pinning patterns is essentially governed by the two rows of z-pins next to the overlap ends. The distance between the edge of the overlap and the adjacent pin row is thus expected to be a critical factor in controlling the fatigue performance of the pinned joints. To explore this aspect, some 2-row pinned joints were manufactured by placing the rows of pins 10 mm away from the overlap edge, instead of the original distance of 4 mm. The joints with this increased pin-to-edge distance were then fatigued under the same testing conditions detailed in Section 2. The fatigue response of the modified pinned joints is compared to that of the unpinned counterparts in the fatigue life graphs of Figure 13. The experimental data show that the fatigue performance of the joints with a pin-edge distance of 10 mm is comparable to or only slightly better than that of the unpinned joints, and thus considerably worse than that of the original z-pinned joints with a 4 mm pin-edge distance. These findings highlight the importance of positioning the pins close to the edges of the joints, in order to activate the bridging action of z-pins in the early stages of crack propagation and thereby take advantage of their beneficial role for a large portion of the fatigue life.

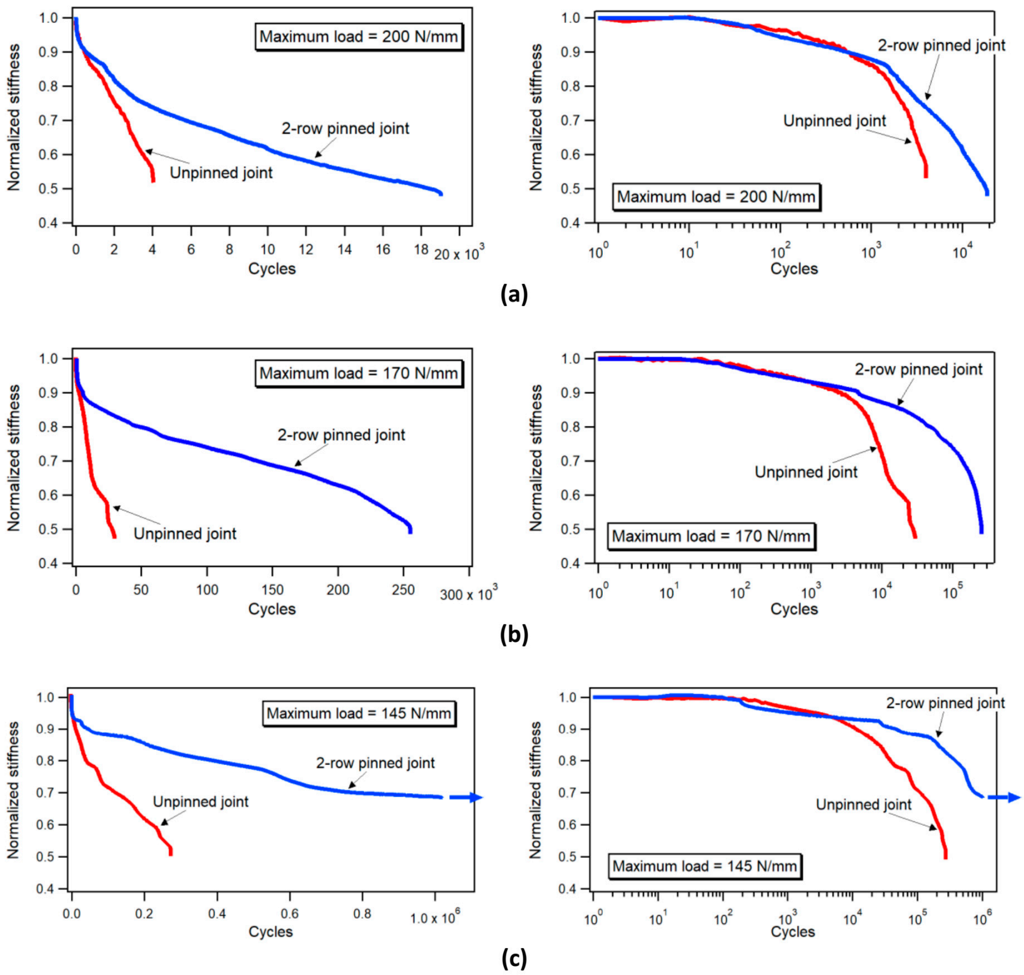

Figure 11. Normalized stiffness vs. fatigue cycles for unpinned and 2-row pinned joints fatigued at maximum loads of 200 N/mm (**a**), 170 N/mm (**b**), and 145 N/mm (**c**). The fatigue cycles are displayed with a linear scale in the graphs on the left and with a logarithmic scale in the graphs on the right. The arrows indicate a run-out test.

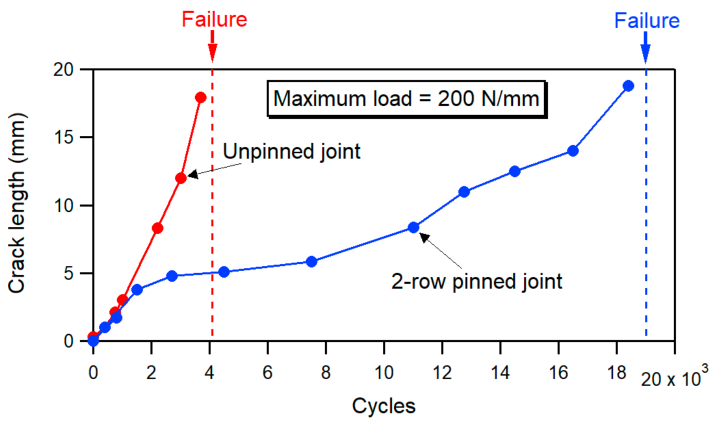

Figure 12. Growth of the major debonding crack with fatigue cycles for unpinned and 2-row pinned joints fatigued at a maximum load of 200 N/mm.

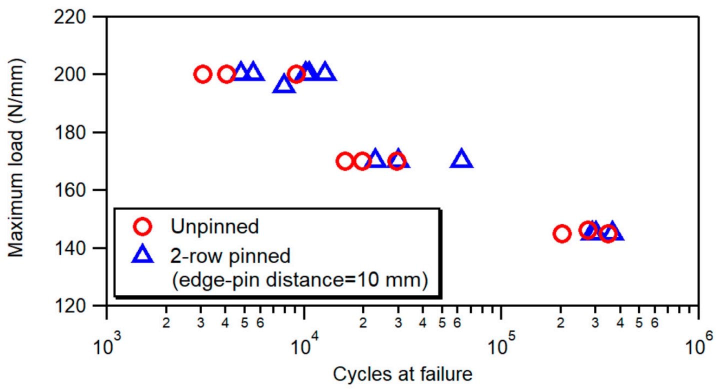

Figure 13. Comparison of the fatigue performance between unpinned joints and 2-row pinned joints with pin rows positioned 10 mm from the overlap edges.

4. Conclusions

The study investigated the effect of three different z-pinning patterns on the static and fatigue response of co-cured step joints between carbon/epoxy adherends. The first type of reinforcing pattern consisted of two rows of steel pins placed close to the overlap edges (2-row pinned joint, with 0.2% pin density). Two other pinning patterns (3-row and 4-row pinned joints) involved the addition of, respectively, one or two extra rows of pins, uniformly distributed over the overlap region. The behavior of the z-pinned joints was compared to that of the reference unpinned counterparts to examine the role of z-pins in enhancing the structural performances of the samples.

The main indications arising from the present investigation are summarized below:

- Z-pinning improves both the static strength and the fatigue lives of the joints.
- The observed increase in static strength (about 15%) and the enhancements in fatigue performance exhibited by z-pinned joints are substantially independent of the number of pin rows.
- Similar damage mechanisms occur in the joints under static and fatigue loads. In both unpinned and pinned joints, damage initiates as a matrix crack at the resin-rich regions between the terminations of the adherends. These cracks subsequently grow as delaminations at the joining interface, until they propagate unstably leading to the ultimate failure.
- The improvements in the structural properties of pinned joints are due to the crack-bridging tractions applied by z-pins, which delay the growth of the debonding crack once it reaches the pins adjacent to the joint edges.

- The presence of z-pins introduces additional energy absorbing mechanisms, such as the frictional pullout of pins, resin crushing, and delamination damage within the adherends, which further enhance the load-bearing capacity and damage tolerance of the joints.
- The fatigue and strength improvements achieved by z-pinning are essentially due to the pins close to the overlap edges.

The findings of the study indicate that proper placement of the pinning reinforcement allows for remarkable improvements in the structural efficiency of composite joints with the insertion of only minimal pin content, thereby preventing or limiting the potential detrimental effects of z-pins. Further analyses are, however, required to explore the improvements achievable using alternative pinning patterns and to characterize the associated toughening mechanisms for different joint geometries and adherend layups.

Author Contributions: Conceptualization, G.L. and F.A.; investigation, G.L., P.B., R.E.M., M.C., D.L., M.E.M. and F.A.; writing—original draft preparation, G.L., P.B., R.E.M., M.C., D.L., M.E.M. and F.A.; writing—review and editing, G.L. and F.A. All authors have read and agreed to the published version of the manuscript reported.

Funding: This research has been developed within the framework of the project eINS- Ecosystem of Innovation for Next Generation Sardinia (cod. ECS 00000038) funded by the Italian Ministry for Research and Education (MUR) under the National Recovery and Resilience Plan (PNRR)—MISSION 4 COMPONENT 2, “From research to business” INVESTMENT 1.5, “Creation and strengthening of Ecosystems of innovation” and construction of “Territorial R&D Leaders”.

Data Availability Statement: The data presented in the paper are available upon request.

Conflicts of Interest: The authors declare no conflicts of interest.

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