# IMPACT DAMAGE RESISTANCE AND TOLERANCE OF Z-PINNED COMPOSITE LAMINATES

Luca Francesconi[1], Gabriela Loi[2] and Francesco Aymerich[2]

[1]Department of Mechanical Engineering, Santa Clara University, Santa Clara, CA, USA
Email: lfrancesconi@scu.edu
[2]Department of Mechanical, Chemical and Materials Engineering, University of Cagliari, Italy
Emails: gabryloi@hotmail.com, francesco.aymerich@dimcm.unica.it

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**Abstract**
The study examines the effect of Z-pinning on the impact and post-impact behaviour of composite laminates. Unpinned and Z-pinned $[0_2/90_2]$s and [0/±45/90]s carbon/epoxy samples were subjected to low-velocity impacts inducing damage states ranging from barely visible damage to full penetration and subsequently tested in compression to examine the influence of Z-pinning on the resistance and tolerance to impact damage. The fracture modes induced by impact and the damage mechanisms controlling the residual compressive properties of the laminates were examined by radiographic and visual inspections. It was found that Z-pinning does not improve the resistance of the laminates to the initiation of delamination under impact loadings. However, Z-pinning enhances the resistance to delamination growth and improves the residual compressive strength of the laminates for impacts of sufficiently high energy. The beneficial effect of Z-pins may be attributed to their bridging action across delaminated interfaces, which reduces the delamination driving force and improves the resistance to local buckling under compressive loads.

## 1. Introduction

Composite laminates exhibit relatively poor strength properties along the out-of-plane direction as compared to in-plane properties. As a result, structures made of composite materials offer a weak resistance to transverse loads and are particularly prone to delaminate when subjected to low-velocity impacts, which are likely to occur during manufacturing, service and maintenance.
Inserting translaminar reinforcements by Z-pinning or stitching, which consist in introducing thin pins or stitches through the thickness of the laminate, is one the most effective approaches to enhance the delamination resistance of composites [1, 2]. The improvements in the delamination resistance provided by through-thickness reinforcements may be attributed to various mechanisms, such as the bridging action or the debonding and pull-out of pins or stitches behind the delamination front [3-5].
While a significant number of studies have been conducted to characterize the structural behaviour of Z-pinned composites [3, 6-10], relatively limited research has been devoted to exploring the effect of Z-pinning on the impact properties of laminated composites. Previous investigations focused on aspects such as the effect of the pinning density [6, 11], of the laminate thickness [12, 13] or of the pins shape [14] on the impact and post-impact performances of laminates. No specific attention has been however devoted to date to the influence of the laminate layup on the impact and residual properties of Z-pinned laminates.
In this study, impact and compression after impact (CAI) tests were performed on unpinned and pinned laminates with cross-ply and quasi-isotropic layups to investigate the role of Z-pinning for enhancing the impact and residual properties of laminates characterized by different patterns and through-thickness distributions of damage.

## 2. Experimental

$[0_2/90_2]$s and $[0/\pm45/90]$s stacking sequences were examined to characterize the effect of Z-pinning on the impact and post-impact performances of the laminates. The two investigated layups have the same number of layers but a different number of interfaces between layers with dissimilar orientations (2 and 6, respectively, for $[0_2/90_2]$s and $[0/\pm45/90]$s layups), thus resulting in significantly different distributions of impact delaminations through the laminate thickness.
The panels were manufactured with Texipreg® HS300/ET223 carbon/epoxy prepreg plies (62% fibre volume fraction) and cured in autoclave under vacuum using a cycle consisting of a 3°C/min ramp, a 2 h hold at 125°C, and a final 4 °C/min ramp down to room temperature. The average thickness of cured panels was 2.5 mm, with no significant difference in thickness between unpinned and pinned laminates. Before consolidation some of the panels were selectively pinned on rectangular areas of 20 mm by 60 mm. The Z-pins, supplied by Albany Engineered Composites, were made of carbon fibres embedded in BMI resin and were driven into the laminates using an hand-held ultrasonic horn. The pins had a diameter of 0.28 mm and were arranged in a square pattern with a spacing of 3.1 mm, resulting in an area density of 2%.
Samples 65 mm by 88 mm in size were finally cut from the panels for impact and CAI testing. The geometry and the Z-reinforced region of pinned samples are illustrated in Fig. 1.

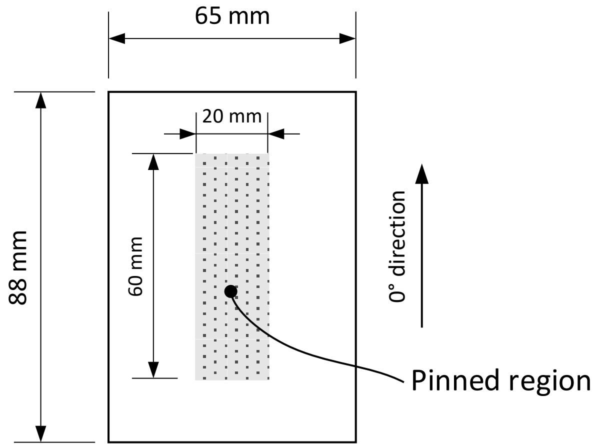


**Figure 1.** Geometry of Z-pinned samples

Impact tests were carried out using a drop-weight impact testing tower with a 2.34 kg impactor. The impactor was provided with a hemispherical indentor of 12.5 mm diameter. A pneumatic catching mechanism was used to capture the impactor after the rebound so as to prevent multiple impacts on the plate. The velocity of the impactor immediately before the impact was obtained by an infra-red sensor, while the contact force between impactor and specimen was measured by means of a semiconductor strain-gage bridge bonded to the impactor rod. During testing, the composite samples were simply supported on a steel plate with a rectangular opening 45 mm x 68 mm in size.

Compression after impact (CAI) tests were carried out using an anti-buckling fixture that supports the two longitudinal sides of the sample during application of the load by knife edges; the sample is also clamped at the top and bottom loading ends.
After impact, the laminates were mounted on the antibuckling system with the 0° direction parallel to the load axis and tested to failure using a 250 kN Instron servoelectric machine with a crosshead speed of 1 mm/min. Small fibreglass end tabs were bonded onto the ends of the samples to avoid or restrain local crushing damage in the loading zone, which is likely to develop, especially with limited impact

damage, because of the small thickness of the laminates.
Damage induced by impact and by compression after impact tests was characterized by X-ray radiography and visual inspections of the surfaces of the samples.

## 3. Results and discussion

Typical force-time traces measured during impacts of increasing energy on unpinned and pinned $[0_2/90_2]$s and [0/±45/90]s samples are presented in Fig. 2.
It is seen that the response of both control and Z-reinforced samples of the two layups greatly depends on the energy of the impact, with force histories exhibiting smooth loading and unloading phases for impacts below a threshold energy, and a large load drop for impacts with energies higher than this threshold. The sudden load decrease was seen to correspond to the onset of perforation, characterized by extensive fibre fracture initiating at the surface layer on the impacted side of the laminate. With increasing impact energy, fibre fractures advance across the layers through the thickness of the laminate until complete penetration of the indentor.
The plots of Fig. 2 also show that while in $[0_2/90_2]$s laminates the value of the force at the first load drop (corresponding to the onset of perforation) is higher in pinned samples than in unpinned samples, in [0/±45/90]s laminates the force level that initiates perforation does not appear to be affected by the presence of Z-pins.

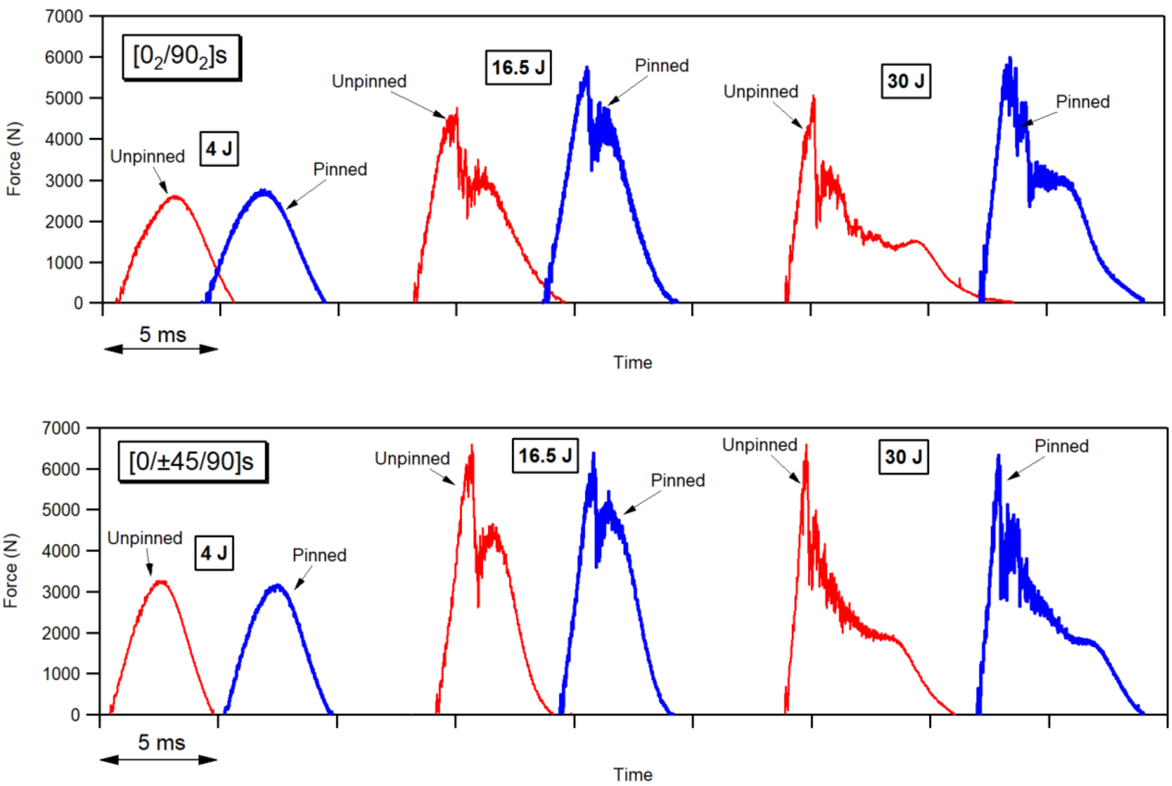


**Figure 2.** Force-time histories measured during impact events on unpinned and pinned samples

The X-radiographs of Fig. 3 compare the damage induced by impact in $[0_2/90_2]$s and [0/±45/90]s laminates.
Damage in $[0_2/90_2]$s samples starts with shear matrix cracks in the 90° layers and a large bending crack in the bottom 0° layers, which trigger the development of a two-lobe delamination at the 90°/0° interface on the tensile side of the sample. The delaminated area grows with increasing impact energy

until fibre damage on the top layer starts the initiation of the perforation stage, which is associated to further propagation of the delaminated area. The comparison of damage induced by impact in unpinned and pinned $[0_2/90_2]$s samples shows that even though Z-pins are not capable of delaying the initiation of delaminations, they significantly reduce delamination size for high-energy impacts.
Initial damage in [0/±45/90]s laminates consists of matrix cracks in the 0° and ±45° layers at the tensile side of the impacted specimens, which trigger two-lobe delamination areas originating at the intersections of these cracks. With higher impact energies, delaminations also develop on the interfaces closer to the impact side, generating a typical staircase damage pattern. The projected damage area is roughly elliptical in both unpinned and pinned samples, but Z-pinned samples exhibit much more irregular delamination boundaries. The perforation stage is again initiated by the unstable growth of fibre fracture from the impacted layer, which leads to a major degradation of the mechanical properties of the laminate, as signalled by the large drop in the force signal. The X-radiographs of damage presented in Fig. 3 show again, similarly to what observed in $[0_2/90_2]$s samples, that the presence of Z-pins does not improve the resistance to the initiation of delaminations, but evidently constrains their subsequent growth for impacts in the high-energy regime.

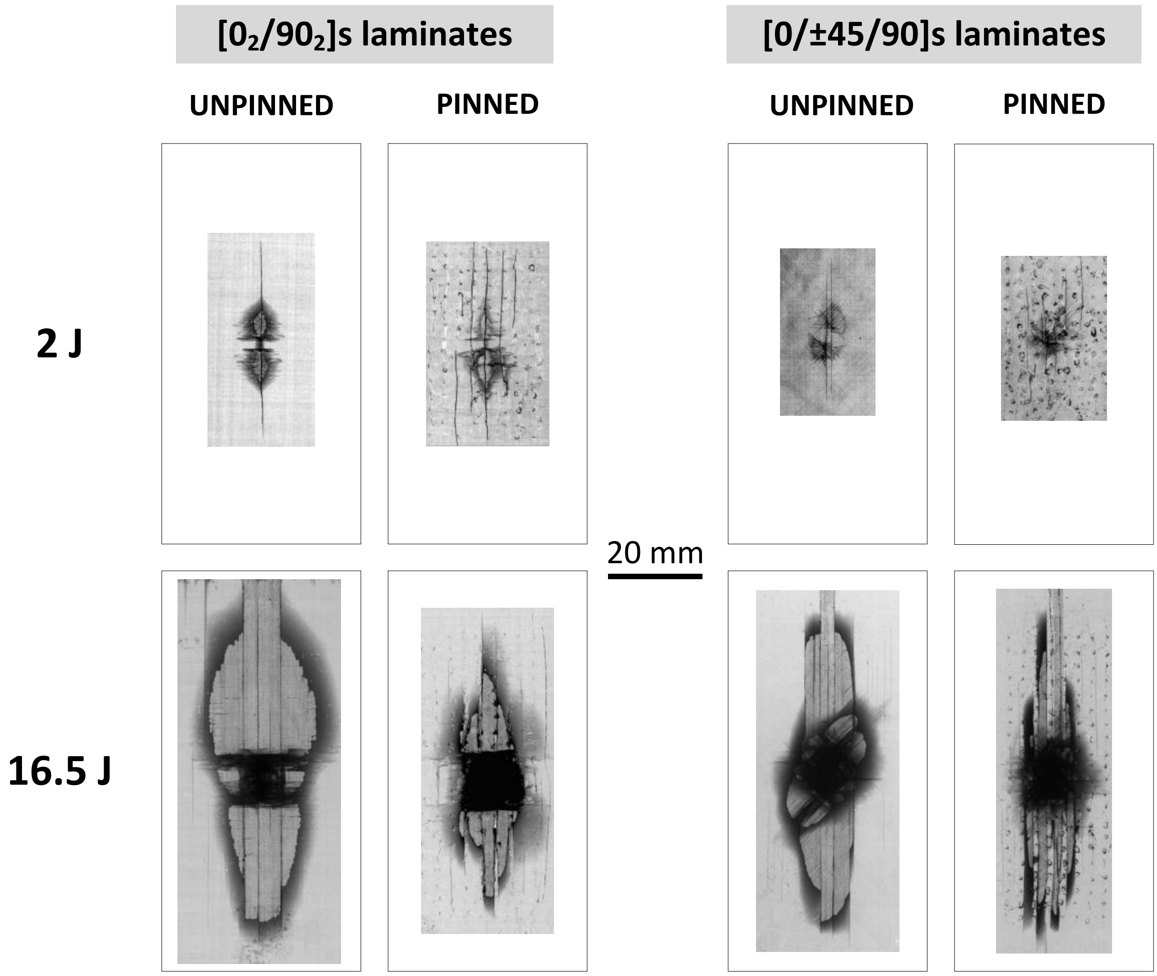


**Figure 3.** X-radiographs of impact damage in unpinned and pinned $[0_2/90_2]$s and [0/±45/90]s laminates

The influence of Z-pinning on the delamination resistance of the two laminate layups may be quantitatively illustrated by the graphs of Fig. 4, which plot the projected delamination area of unpinned and pinned samples as a function of impact energy. We may see that Z-pins have no effect for low impact energies (i.e. for damage areas below a certain threshold size), while their effectiveness increases with increasing impact energy when the damage area is above this threshold. This trend may be explained by the fact that Z-pins bridging delaminated interfaces may effectively reduce the stresses at the crack tip only in the presence of delaminations sufficiently large to effectively activate their potential closing action [4].

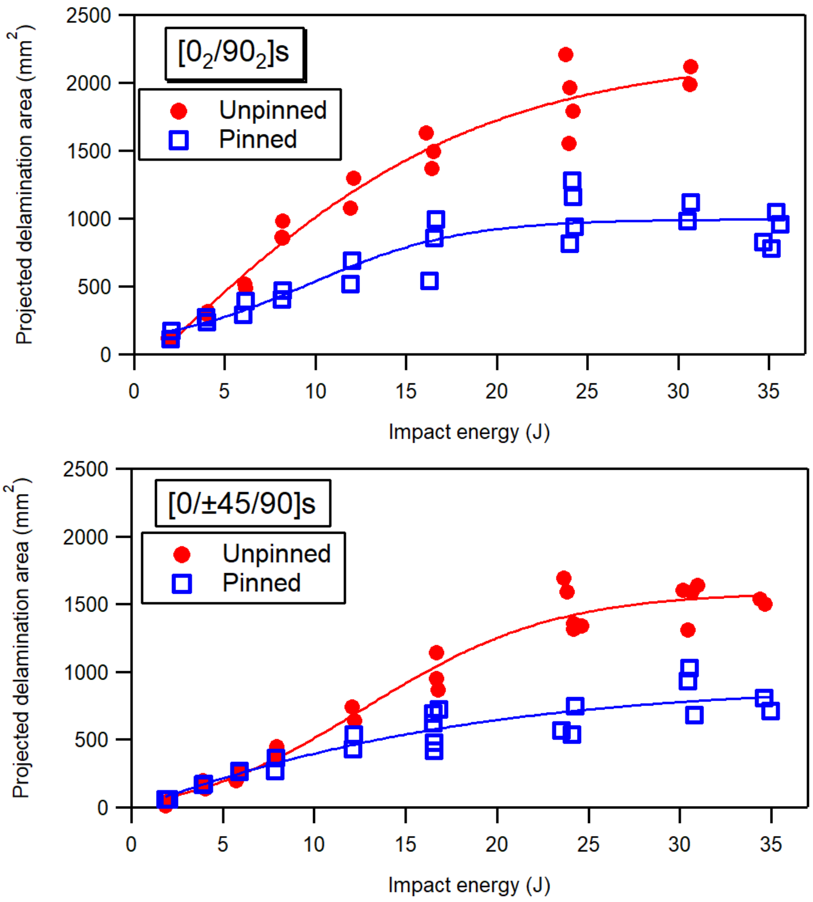


**Figure 4.** Damage area vs impact energy for unpinned and pinned [$0_2/90_2$]s and [0/±45/90]s laminates

After impact, unpinned and pinned samples of both stacking sequences were tested in compression up to failure to examine the influence of Z-pinning on the residual strength and damage tolerance of the two laminates.
The graphs of Fig. 5 show the CAI strength (defined as the maximum load attained during the test divided by the cross-sectional area of the sample) of impacted [$0_2/90_2$]s and [0/±45/90]s samples plotted versus impact energy. Despite the large scatter, which is typical of CAI tests, the experimental results show an evident reduction in compressive strength with impact energy, thus indicating that damage induced by impact has a significant effect on the structural performance of the laminates. In particular, both unpinned and pinned samples of the two layups exhibit a steady decrease in strength with increasing impact energy for impacts below the perforation threshold, while the compressive strength remains approximately constant for impacts in the perforation/penetration range. It is worth remarking that this trend is similar to that exhibited by the damage area as a function of impact energy (see the graphs of Fig. 4), which is characterized by an initial rapid rise followed by a region with a much slower increase
We may also notice that the CAI strength of pinned samples is comparable or lower than that of unpinned samples for low impact energies, while Z-pins begin to improve the post-impact compressive performance of the laminates only from the impact energy level at which they also start to reduce the impact delamination area (i.e. from impact energies of approximately 6 J and 12 J for [$0_2/90_2$]s and [0/±45/90]s laminates, respectively).
The data shown in the graphs of Fig. 5 indicate for example that Z-pinned samples have approximately

a 15-20% increase in compression strength after impact over the perforation/penetration range as compared to analogous unpinned laminates.
The higher CAI strengths exhibited by Z-pinned laminates for sufficiently high impact energies may be attributed not only to the reduction in the delamination area induced by impact, but also to the increased resistance to delamination growth and to local buckling of delaminated regions provided by Z-pinning. Examinations of the two surfaces of the samples during CAI tests and visual and radiographic inspections (Figs. 6, 7) of the failed laminates indicate that the strength of unpinned laminates is mainly controlled by the local buckling of sublaminates at delaminated regions, which promotes the growth of existing delaminations from the impact region to the edges of the samples; collapse of the laminates is caused by fibre kinking failures, which typically start at the edge of the delaminated area and propagate transversally across the lateral ligaments of the laminate. In pinned laminates, in contrast, the bridging action of Z-pins suppresses or delays the buckling of sublaminates and the growth of existing delaminations, and the final failure is triggered by fibre kinking starting from pre-existing broken fibres at the indentation area. Fibre failures by micro-buckling advance in steps over the load-carrying section of the samples, following a fracture path that always runs along rows of pins in the direction transverse to the loading axis.

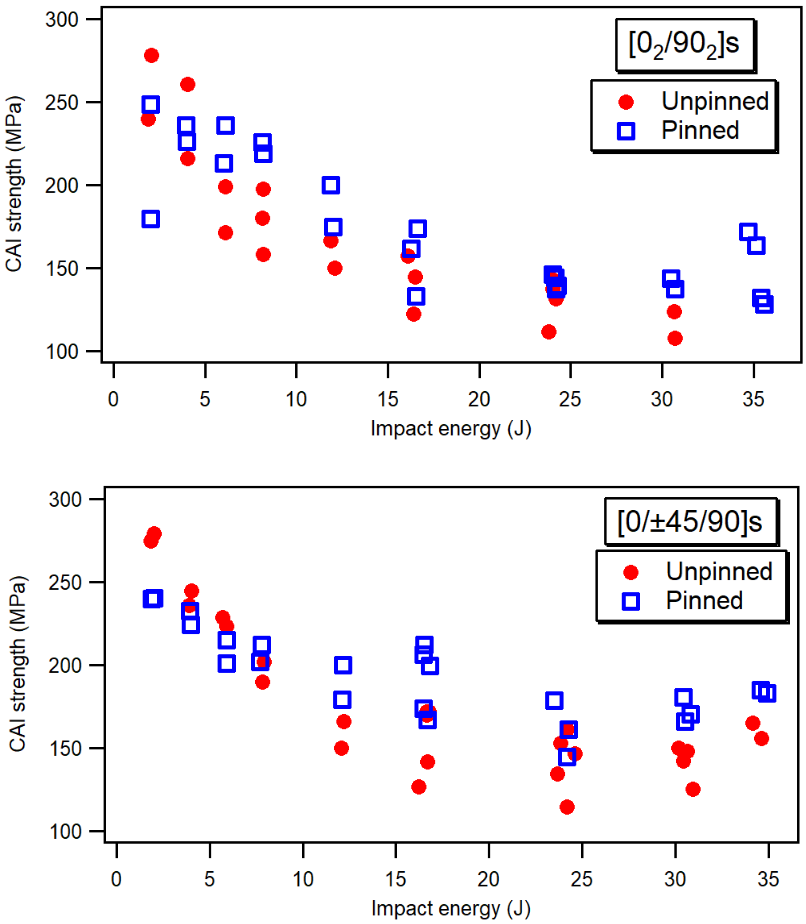


**Figure 5.** CAI strength vs impact energy of [$0_2/90_2$]s and [0/±45/90]s impacted samples

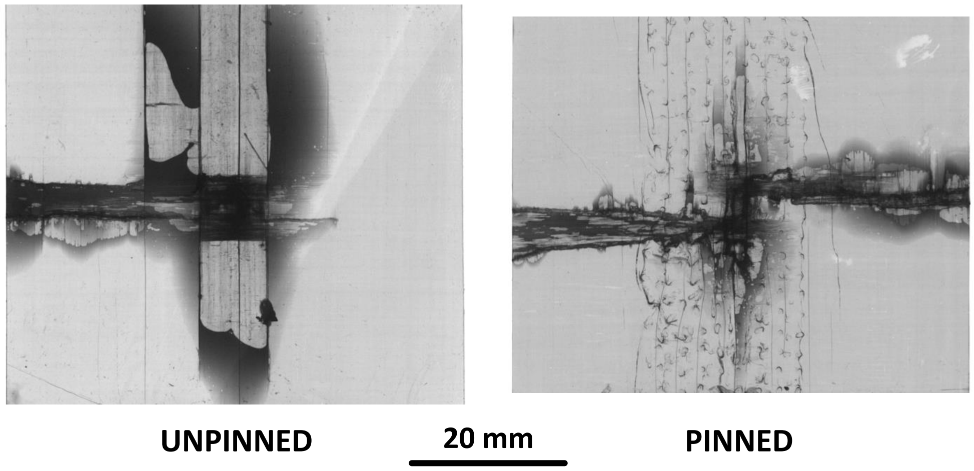


**Figure 6.** X-radiographs of damage after CAI testing in unpinned and pinned $[0_2/90_2]$s laminates impacted at 16.5 J.

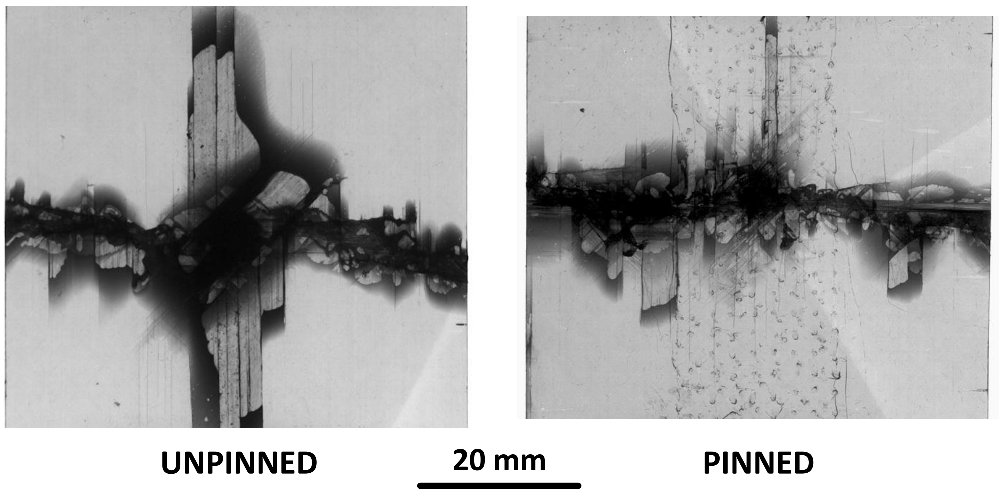


**Figure 7.** X-radiographs of damage after CAI testing in unpinned and pinned [0/±45/90]s laminates impacted at 16.5 J.

## 4. Conclusions

The influence of Z-pinning on the impact and post impact compressive behaviour of two carbon/epoxy laminates ($[0_2/90_2]$s and [0/±45/90]s) subjected to low-velocity impact was investigated in this study. The following conclusions may be drawn on the basis of the experimental observations:

- Z-pinning is not able to delay the onset of delamination damage, but improves significantly the resistance to the growth of the delaminations as soon as they reach a size sufficiently large to activate the bridging action of pins.
- The response to impact of unpinned and pinned samples exhibits a sudden load drop when they are impacted with energies higher than a threshold level; this load drop corresponds to the initiation of the perforation stage.
- Z-pinning improves the CAI strength of samples impacted with energies in the perforation/penetration range, while pinned samples have comparable or even lower strengths than analogous unpinned samples when impacted at low energies.

- The CAI failure of unpinned laminates is controlled by local buckling of sublaminates and delamination growth, which promote the formation of fibre kink-bands propagating across the undamaged ligaments of the samples. In pinned laminates, by contrast, Z-pins increase the resistance to local buckling of the damaged regions and constrains the growth of impact delaminations; fibre kinking failures are initiated at sites of existing broken fibres in the indentation area and advance in steps over the load-carrying section until ultimate failure.

## Acknowledgments

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