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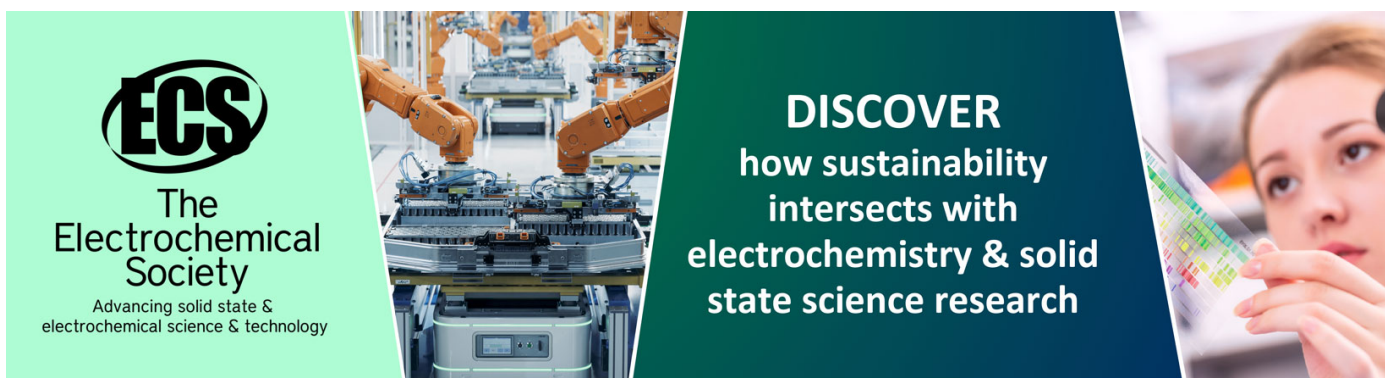
Impact damage resistance of thin stitched carbon/epoxy laminates

To cite this article: L Francesconi and F Aymerich 2015 *J. Phys.: Conf. Ser.* **628** 012099

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Impact damage resistance of thin stitched carbon/epoxy laminates

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Abstract. The study examines the influence of through-thickness stitching on the damage response of thin cross-ply carbon/epoxy laminates subjected to low-velocity impacts. Instrumented impact tests were carried out on unstitched and polyethylene stitched laminates and the resulting damage was assessed in detail by X-radiography analyses. The results of the observations carried out during the experimental analyses are illustrated and discussed to identify the mechanical role played by through-thickness reinforcement and to highlight the influence of the laminate layup on the impact resistance of stitched laminates.

1. Introduction

Delamination, i.e. separation between layers that occurs by failure of the resin rich interlaminar interface, is the most common failure mode in laminated composites, as a consequence of their inherent weakness in the thickness direction due to the lack of out-of-plane fibrous reinforcement [1]. The presence of internal delaminations may reduce considerably, especially under compressive loads, the structural integrity and the load bearing capacity of composite structures [2]. Delaminations induced by low-velocity impacts are of primary concern, since impact damage is often difficult or impossible to detect by visual inspection of the surface (Barely Visible Impact Damage – BVID). Preventing the initiation of delaminations and delaying their propagation are thus key strategies for the improvement of the reliability and lifetime of laminated composite structures.

Various approaches have been proposed in the last decades to improve delamination resistance of composite laminates [3-7]. They include the increase of interfacial strength between fibre and matrix, the adoption of high-toughness resins, the insertion of adhesive or nano-modified films between layers (interleaving), the introduction of through-thickness reinforcement by stitching or Z-pinning. Among them, the insertion of translaminar (Z direction) reinforcements by stitching has proven to be a successful strategy for the enhancement of the interlaminar properties in composite laminates.

Stitching is a technique which consists in sewing a continuous reinforcing thread through an uncured pre-preg laminate or fabric pre-form before the consolidation or impregnation phase [5]. As demonstrated by numerous studies [8,9], the bridging mechanism provided by stitches across delamination cracks reduces significantly relative opening and tangential displacements of the delaminated layers, thus limiting the interlaminar stresses at the crack tip and increasing the intrinsic resistance of the material to delamination growth. It should be remarked, however, that the stitching



process inevitably perturbs the original material architecture in the vicinity of stitches, inducing localized defects such as resin rich regions, fibre misalignment and fibre breakage that may act as stress concentration and damage initiation sites and seriously degrade in-plane and flexural properties of the base laminates.

A number of studies have been conducted on the effect of stitching on the impact response of composite laminates [10-17]. However, because of the influence of many factors, such as thread and composite materials, stitching density and pattern, laminate layup and thickness, manufacturing procedures, the general role played by stitches in controlling the damage response of impacted laminates has not yet been completely characterized and described.

In this study, a series of experimental analyses have been carried out to investigate and compare the behaviour of thin unstitched and stitched cross-ply laminates under low-velocity impact. The main findings of the analyses are illustrated and discussed to assess the effect of through-thickness stitches on damage evolution, delamination resistance and structural performance of the examined laminates.

2. Experimental

Cross-ply $[0_2/90_2]_s$ laminated panels were manufactured using unidirectional carbon/epoxy prepreg tapes (Seal Texipreg® HS160/REM). Before curing, some of the panels were stitched using twisted polyethylene rovings (3x200 dtex Dyneema® SK60) by an industrial sewing machine. The panels were stitched perpendicularly to the 0° direction of the laminate, and both the distance between consecutive stitches along the stitching line (stitch step) and that between two adjacent stitching lines (stitch row spacing) were kept at 5 mm. A modified lock stitch, where the intersection between the upper needle thread and the lower bobbin thread occurs at the surface of laminate was adopted in order to reduce distortion within the laminate. Both unstitched (base) and stitched panels were vacuum bagged and cured in a hydraulic hot press under a pressure of 5 bar. The temperature curing cycle consisted of an initial $1.5^\circ\text{C}/\text{min}$ ramp followed by a 2 h hold at 125°C and a ramp down to room temperature at a rate of $1^\circ\text{C}/\text{min}$. The final thickness of cured panels was 1.2 mm. No significant difference in thickness was observed between unstitched and stitched panels after curing.

Type A and type B rectangular samples $65\text{ mm} \times 87.5\text{ mm}$ in size were finally obtained for impact testing by cutting the consolidated plates with the orientations schematically indicated in Figure 1 with reference to stitched samples. As visible in Figure 1, type A and type B samples were cut with their long sides respectively parallel and perpendicular to the 0° direction of the laminated panel. With respect to the direction of the long side of the samples, the layups of the two classes of samples were thus $[0_2/90_2]_s$ (type A) and $[90_2/0_2]_s$ (type B).

Impact tests were conducted using an instrumented drop-weight testing machine with a 2.28 kg impactor, equipped with a hemispherically-ended rod of 12.5 mm in diameter. The velocity of the impactor immediately before and after 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-gauge bridge bonded to the impactor rod. The velocity and the displacement of the impactor were obtained by integration of the contact force signal.

During impact, the specimens were supported by a steel plate having a rectangular cutout $45\text{ mm} \times 67.5\text{ mm}$ in size. The rectangular samples were always placed on the support with their long sides parallel to the long sides of the cutout.

Stitched and unstitched laminates were impacted at the central point of the sample with energies ranging between approximately 1 J and 9 J, obtained by varying the drop height of the impactor. The corresponding impact velocities ranged between 0.9 m/s and 2.8 m/s. All stitched samples were impacted on the side where the needle thread loops with the bobbin thread to form the stitch. Impact damage was characterized by penetrant enhanced X-radiography and by direct observation of the surfaces of the samples.

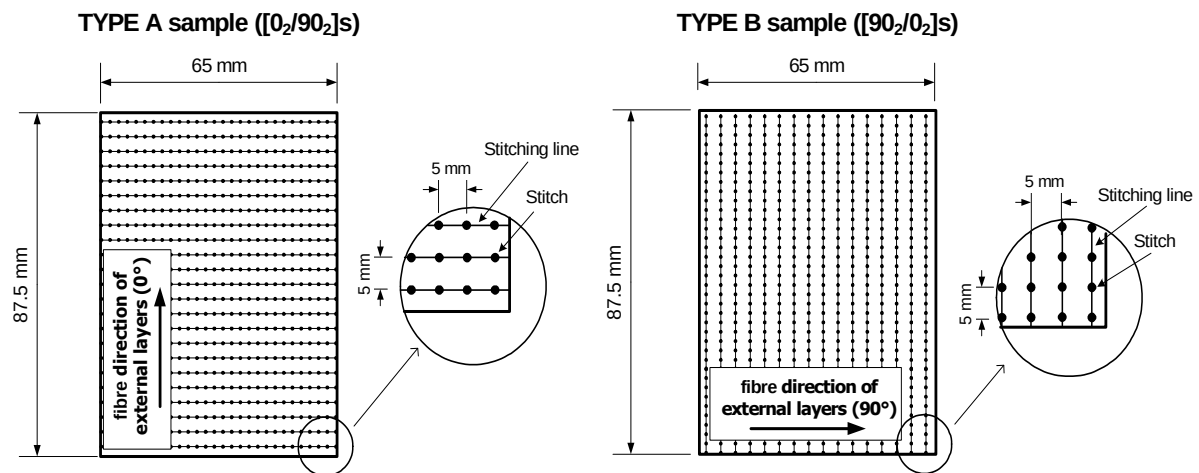


Figure 1. Stitching pattern of Type A and Type B samples

3. Experimental results and discussion

Figure 2 show force-time histories and force-displacement curves for unstitched and stitched type A samples impacted at two impact energies. It is seen that force-displacement plots are highly nonlinear, with a continuous increase in stiffness up to a deflection of about 3 mm, as a direct consequence of the low thickness of the laminate [17]. Unstitched and stitched samples exhibit analogous impact responses, with no evident irregularities in the force trace, for impacts with energies below a threshold value of about 6 J. When the impact energy exceeds this threshold, a major force drop is observed at a force level of about 3 kN in both unstitched and stitched laminates (Figure 2).

Figure 3 shows representative radiographs of damage induced by impact in unstitched and stitched type A laminates for two levels of impact energy (5 J and 7 J). Damage starts at impact energies lower than 1 J and consists of bending and shear matrix cracks that develop respectively in the bottom 0° layers and in the middle 90° layers; a delamination is then triggered at the intersection between matrix cracks on the $90^\circ/0^\circ$ interface closer to the tensile side of the sample. With increasing impact energies, the delaminated area grows in size, mainly propagating along the fibre orientation of the lower ply of the interface (0° direction) with a characteristic two-lobed shape. For impact energies higher than 6 J, the delaminated area of unstitched samples experiences a sudden and unstable growth towards the edges of the sample, finally inducing significant fibre fracture on the 0° layers. In stitched samples, major fibre breakage is again observed on the 0° layers, but the delaminated area measured after impact is significantly smaller than in unstitched samples. The sharp load drop recorded during the impact tests (see the plots of Figure 2) corresponds to the unstable growth of delamination and the onset of major fibre damage mechanisms occurring in the samples.

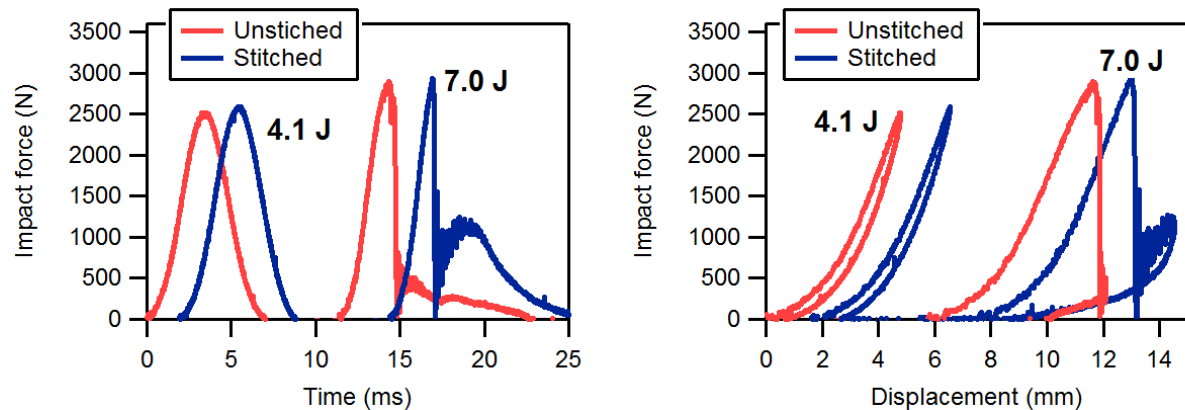


Figure 2. Force-time (left) and force-displacement (right) curves for unstitched and stitched type A samples

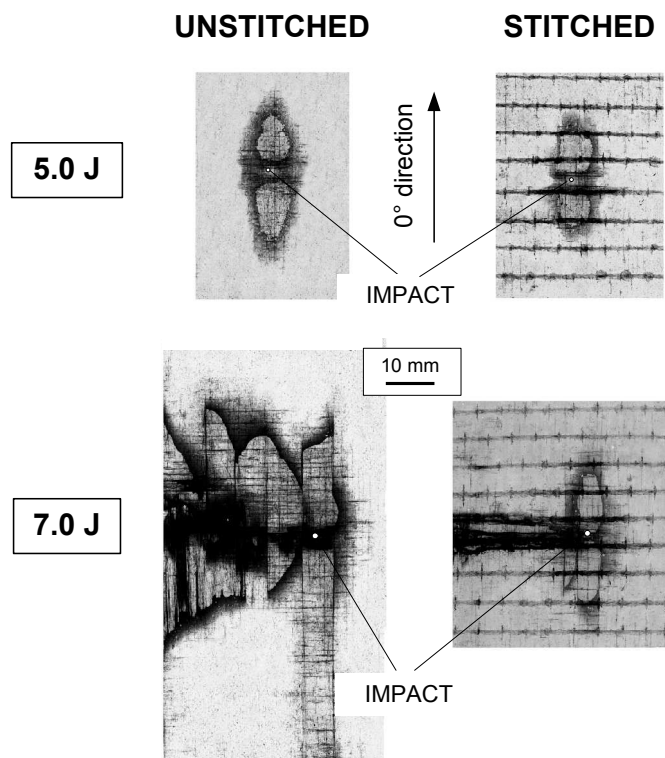


Figure 3. X-radiographs of impact damage in unstitched and stitched type A samples

The analysis of the damage patterns as obtained by X-radiography indicates that, while stitching does not modify the basic mechanisms of impact damage, it substantially reduces the area of the delamination induced by impact. The graph of Figure 4, which plots the values of the projected delaminated area measured after impact as a function of impact energy, shows that the delaminated areas of stitched samples are, on average, approximately 70% those of unstitched samples for impacts with energies up to 6 J; the reduction of the delamination size is even larger for impacts with energies higher than 6 J, with delaminated areas of stitched samples roughly one-half those of unstitched samples.

The influence of stitching on the damage resistance of type A laminates may be further examined with reference to the impact response under high-energy impacts. When the threshold 3 kN load for unstable damage propagation is exceeded, in unstitched laminates the delaminated area first propagates - in the form of a delaminated strip oriented along the 0° direction - up to the short side of the sample, and afterwards extends across the sample width along the 90° direction. When the size of the delaminated area reaches a critical extent, the load-carrying 0° plies are no longer capable of sustaining the applied load, leading to extensive fibre fracture of the top and bottom 0° layers of the sample (Figure 3, impact energy = 7 J). In stitched specimens, in contrast, the presence of stitches greatly inhibits the propagation of the delamination along both the 0° and 90° directions, thus resulting in a substantially smaller delaminated area as compared to unstitched samples (Figure 3, impact energy = 7 J). However, the stress concentration in the vicinity of stitches is sufficient to promote the onset and growth of fibre fracture, which is observed to start at stitch locations and to propagate along a path linking contiguous stitches.

The differences in the structural response and dissipative behaviour of unstitched and stitched type A laminates under high energy impacts may be also explored by the analysis of the plots of Figure 5, which show histories of the contact force and of the energy of the impactor for a 7 J impact energy. We may see that while in unstitched laminates the initial energy is almost entirely dissipated during the impact, in stitched samples a considerable portion of the initial impact energy is transferred back to the impactor after the rebound. This suggests that stitched samples may provide better post-impact properties and residual structural capacity than unstitched ones even in the presence of extensive and widespread damage as that induced by high-energy impacts.

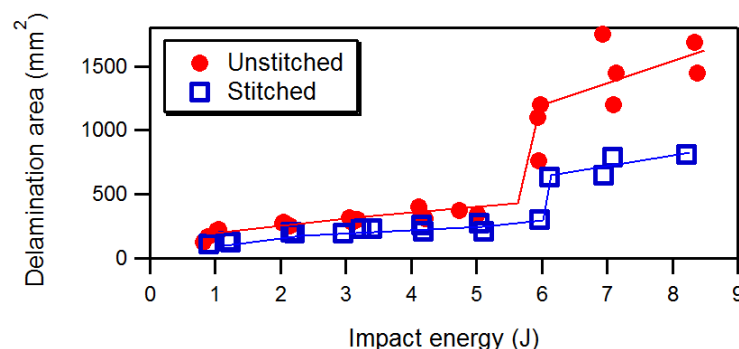


Figure 4. Projected delamination area vs impact energy for unstitched and stitched type A samples

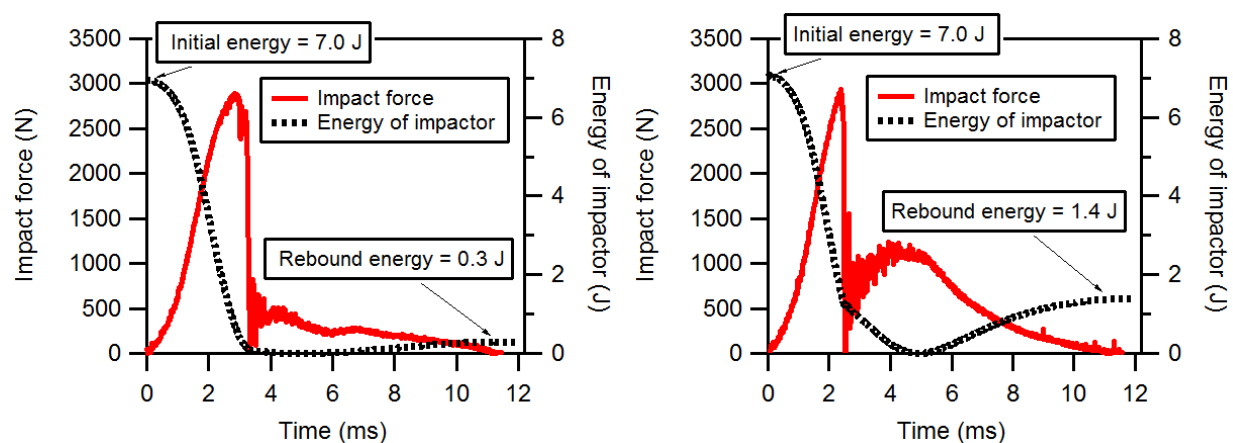


Figure 5. Histories of contact force and energy of impactor during impacts on unstitched (left) and stitched (right) type A samples

Typical force-time and force-displacement plots for unstitched and stitched type B samples impacted at approximately 3 J and 5 J energy are shown in Figure 6. Similarly to type A samples, the response of type B laminates is characterized by a continuous increase in slope with increasing out-of-plane displacement, due to membrane effects induced by large laminate deflections. Comparable force-time and force-displacement curves can be observed for unstitched and stitched samples for impacts up to about 3 J energy. Above this energy level, a sudden load decrease is experienced by unstitched samples at a load level slightly higher than 2 kN, while a comparable load drop can be observed in stitched samples only at a significantly higher load (approximately 2.5 kN).

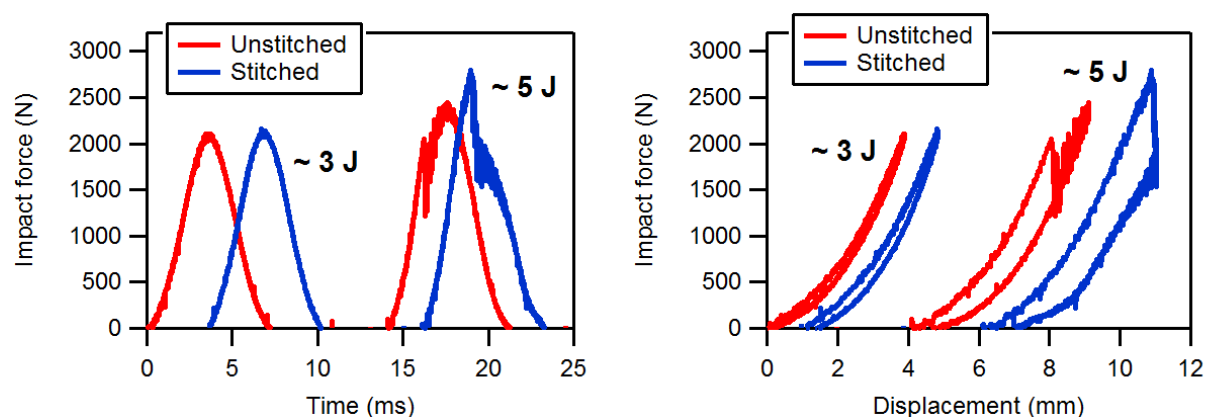


Figure 6. Force-time(left) and force-displacement (right) curves for unstitched and stitched type B samples

Representative impact damage scenarios occurring in type B samples are illustrated in the X-radiographs of Figure 7. Damage initiates at impact energies below 1 J as tensile matrix cracks in the bottom 90° layers and as shear matrix cracks around the contact area in mid 0° layers. Matrix cracking is followed by a two-lobe delamination that develops on the adjacent 0/90 interface and propagates along the fibre direction of the lower ply of the interface (90° direction). When unstitched samples are impacted with an energy exceeding a threshold value of about 3 J, the delamination exhibits an unstable growth, developing into a rectangular shape and quickly propagating to one edge of the specimen, with a damage evolution similar to that observed in unstitched type A laminates. The onset of the phase of unstable damage development is signalled by the load drop feature visible in the force-time and in the force-displacement traces.

In stitched laminates, as expected, the bridging effect of stitches hinders the growth of the two-lobe delaminated area, thus delaying the unstable propagation of the delamination and increasing the critical load at which the force signal exhibits the sudden load drop. However, the stress concentration induced by stitches promote the initiation of local delaminations at multiple stitch locations. Under increasing impact loads, local delaminations tend to coalesce and propagate following the direction of the stitching lines (Figure 7). This behaviour explains why, in type B samples, in spite of the beneficial effect of stitches, the projected delamination area of stitched laminates is only marginally smaller than that of analogous unstitched samples, as visible in the plot of Figure 8.

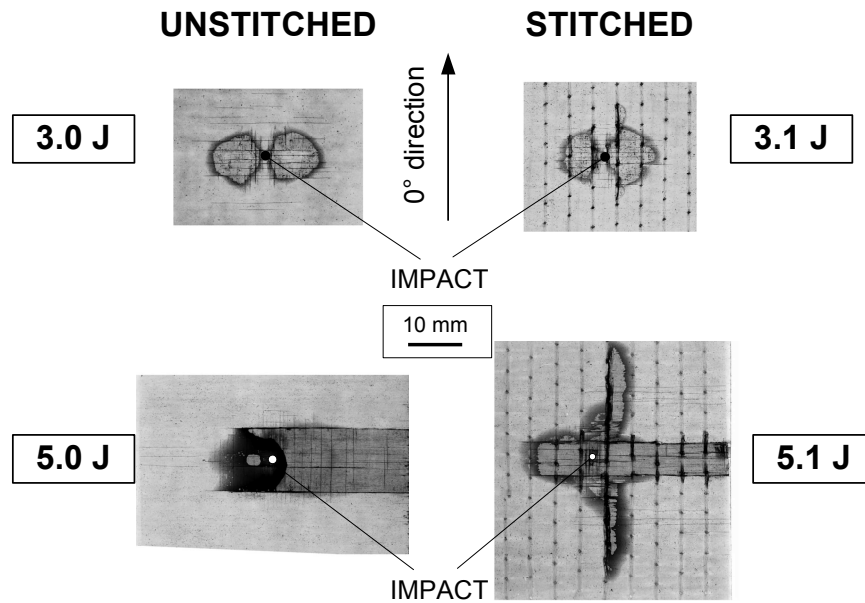


Figure 7. X-radiographs of impact damage in unstitched and stitched type B samples

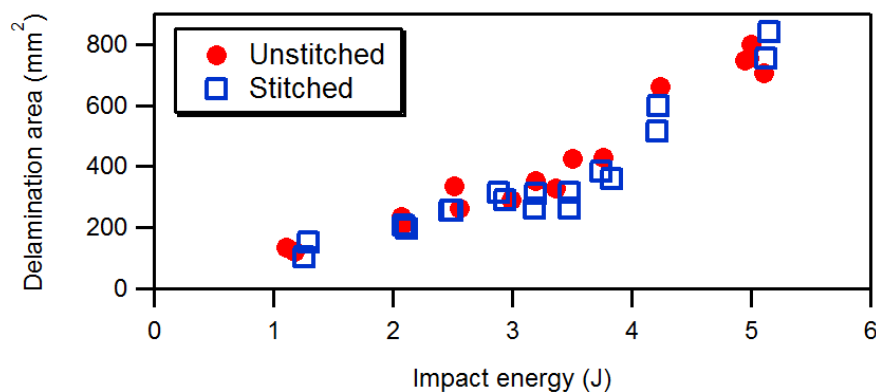


Figure 8. Projected delamination area vs impact energy for unstitched and stitched type B samples

4. Conclusion

The influence of through-thickness stitching on the structural and damage response of two classes of cross-ply carbon/epoxy laminates ($[0_2/90_2]_s$ and $[90_2/0_2]_s$) subjected to low-velocity impact was investigated in this study. It was found that the efficiency of stitching in improving the resistance to delamination of the laminates is affected by the orientation of the layers with respect to the loading configuration. In particular, while stitching greatly improved the delamination resistance of type A ($[0_2/90_2]_s$) laminates, similar sizes of delaminated area were measured after impact in unstitched and stitched type B ($[90_2/0_2]_s$) laminates, due to the growing of delaminations at multiple stitch locations.

These findings indicate that design procedures for primary structural elements based on stitched composites should also account for the sensitivity of the specific layup to individual failure modes potentially triggered by the presence of through-thickness reinforcements.

Acknowledgments

The support of the Regional Government of Sardinia through grant CRP-60404-2012 (*L.R.* 7, 2007) is gratefully acknowledged

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