A NUMERICAL-EXPERIMENTAL STUDY OF THE DAMAGE RESPONSE OF STITCHED COMPOSITE LAMINATES TO LOW VELOCITY IMPACT

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Abstract
This study examines the effect of stitching on the structural and damage response of $[0_3/90_3]_s$ and $[0/90]_{3s}$ carbon/epoxy laminates subjected to low-velocity impact. The commercial finite element code Abaqus was used to model the laminates and to simulate the progression of the internal damage under impact. Intralaminar (fibre breakage and matrix fracture) and interlaminar (delamination) damage modes were introduced in the simulations of the stitched and the unstitched plates by the use of energy-based continuum damage models. The results of the FE simulations were compared with the force-deflection data and the damage maps obtained experimentally by radiographic analyses. The numerical results are in good agreement with the experimental observations, both in terms of structural response of the laminates and of shape and size and of internal damage.

1. Introduction

The utilization of fibre reinforced composite materials has become increasingly popular in many engineering fields, ranging from the aerospace and wind energy industries to the road, railway and marine transport sectors. The high specific static strength and the remarkable fatigue resistance make these materials very attractive in many fields, where lightness and good mechanical properties are of primary importance.

However, while conventional laminated composites usually exhibit excellent in-plane mechanical properties, they are characterized by a high sensitivity to out-of-plane or impact loads, as a consequence of the lack of through-thickness reinforcement. This can easily lead to the initiation and propagation of interlaminar cracks (delaminations) at the interfaces between layers with different local orientations; delamination damage is a major concern in composite design, since it may severely affect the load carrying capability, as a result of instabilities or crack propagation, especially under compressive loads.

For this reason, several methods have been proposed to improve the interlaminar fracture resistance of composite structures. They include matrix toughening, enhancement of the fibre-matrix adhesion, interleaving [1], use of short-fibre interlaminar reinforcement [2], through-thickness stitching and Z-pinning [3].

Stitching, which consists in sewing a fibre thread (usually glass, Kevlar® or polyethylene fibres) through a stack of uncured prepreg tapes or of dry fabric layers before curing the prepreg or injecting the resin into the fabric preform [3], has proven to be one of the most effective approaches to enhance the interlaminar properties of laminates. Stitching was found to increase the delamination resistance of

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laminates under static and impact loadings [4], and to improve the tolerance to damage and the residual strength of impacted laminates under compressive or tensile loads [5].
In contrast, the stitching process leads to a distortion of the inner structure of the laminate, introducing local flaws and stress concentration regions, which may act as starting points for additional damage modes in the material.
A significant number of papers have been dedicated to the experimental characterization of the structural and damage response of stitched laminates to low-velocity impact. Most of these studies [5-9] show that the introduction of through-thickness stitches reduces the delamination area caused by impact, as a consequence of the improvement of interlaminar fracture properties of the material. Significant reductions of the delaminated area were also observed in [10-12] in pre-preg carbon/epoxy laminates stitched with Kevlar or polyethylene threads and subjected to impacts of various energies In particular, it was found that whereas stitching does not inhibit the initiation of delaminations, it induces a clear reduction of damage area for delaminations sufficiently long to activate the bridging action of stitches. It was also seen that the efficiency of the toughening mechanisms introduced by stitching strongly depends on the extent and nature of the impact damage occurring in the base unstitched laminate [11].
As compared to the amount of experimental investigations, the published research on the simulation of the effect of stitching on the damage response of composite laminates under impact loading is more limited [5, 8, 13]. There is thus a need for the development and validation of modelling strategies capable of providing accurate and reliable predictions of the damage induced by impact on stitched composite structures.
In this paper, the effect of stitching on the response of laminated plates to low-velocity impact is investigated by a nonlinear FE model based on the use of progressive damage schemes. The results of the FE analyses are discussed and compared with experimental data obtained by drop-weight impact tests on unstitched and stitched laminates with two cross-ply lay-ups.

2. Experimental

2.1 Materials and impact testing

A series of experimental data acquired in previous studies of the impact response of stitched and unstitched $[0_3/90_3]_S$ and $[0/90]_{3S}$ laminates [10, 11] were used as a benchmark to compare and verify the quality of the FE simulations.
The laminates were made of unidirectional Seal HS160/REM carbon epoxy prepreg tapes and stitched with Kevlar 29 untwisted rovings. The Kevlar threads were sewn perpendicular to the direction of the 0° layers with a stitch step (distance between consecutive stitches along stitching lines) and a stitch spacing (distance between two adjacent stitching rows) of 5 mm. Both stitched and unstitched laminated plates were vacuum bagged and consolidated in autoclave. Specimens 65 mm × 87.5 mm in size and with an average thickness of 2 mm were cut from the plates for impact testing.
An instrumented drop-weight impact testing machine provided with a 2.28 kg impactor was used to impact the laminates. During impact testing, the samples were simply supported on a steel plate having a 45 mm × 67.5 mm rectangular opening. A velocity sensor was used to measure the velocity of the impactor immediately before the contact and at the rebound. The indentor displacement was evaluated by double integration of the contact force signal, obtained by a strain-gauge bridge bonded to the tup of the impactor. Barely Visible Impact Damage (BVID) scenarios, as characterized by impact energies lower than approximately 7 J, were examined in this study.

2.2 Experimental results

Experimental observations show that stitching does not significantly affect the global structural response to impact of $[0_3/90_3]_S$ and $[0/90]_{3S}$ laminated samples, as indicated by the main features of the force-time and force-deflection curves.
Damage in clustered $[0_3/90_3]_S$ laminates initiates as tensile and shear matrix cracks, which trigger the development of a main large delamination at the 90°/0°interface, farthest from the impact side. Fibre fracture is observed only for impact energies above 8 J on 0° layers at the impact side of the laminate.

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A significant reduction in the delaminated area is achieved by stitching for impact energies higher than about 3 J.
Damage in dispersed $[0/90]_{3S}$ laminates is characterized by a pattern of smaller overlapping delaminations, which develop at multiple interfaces through the laminate thickness. Unlike in clustered $[0_3/90_3]_S$ laminates, there is no evident increase in the delamination resistance of dispersed $[0/90]_{3S}$ samples after stitching; fibre fracture was observed around the indentation area for impacts with energies higher than about 3 J.

3. Finite element model

The commercial FE code ABAQUS/Explicit was used to simulate the impact events on the laminated samples. Fig. 1 shows the mesh of the FE model of the laminate and of the hemispherical impactor. C3D8R solid elements were used to model the individual plies of the laminates, with one element per ply through the laminate thickness. COH3D8 cohesive elements, inserted at the interfaces between layers with different fibre orientations, were used to model interlaminar damage. To avoid compenetration between delaminated layers the cohesive elements were not removed from the FE model after failure.
Elements with in-plane size of 0.5 mm by 0.5 mm were chosen after a sensitivity analysis that showed convergence of FE solutions for elements smaller than this size.
The contact between the sample and the indentor and between the sample and the rigid supporting plate was simulated by surface-to-surface contact pairs enforced by a penalty approach. A Coulomb friction model with a friction coefficient equal to 0.3 was included in the contact formulation. Both the impactor and the supporting plate were modelled with R3D4 rigid elements. No mass scaling was used in the analyses.
Energy-based continuum damage mechanics models were adopted for prediction of intralaminar damage in the laminate layers. The onset of individual tensile or compressive fibre and matrix failure modes was predicted by means of specific stress/strain based initiation criteria, while the subsequent progressive stiffness degradation was simulated through fracture energy based evolution laws; a phenomenological relation was used to account for the nonlinear behaviour exhibited by the material under shear loading.
Interlaminar damage was simulated by interface cohesive elements, defined by a traction–separation constitutive law that consists of an initial linear elastic phase until damage onset, followed by a linear softening stage representing the progressive decohesion of the interface with increasing damage. Complete fracture of the interface is assumed to occur when cohesive tractions vanish at the end of the degradation phase. The effect of compressive stress on the mode II fracture energy was accounted for in the analyses by the failure criterion proposed in [14].
A detailed illustration of the formulations of the models used in the FE analyses may be found in [15].
The bridging action of Kevlar stitches was modelled by elastic C3D8R elements inserted along the thickness of the laminate and embedded within the laminate layers. Cohesive elements were interposed between the stitches and the adjacent layer elements to model the resistance provided by the resin rich region to the lateral ploughing of the stitches and to simulate the potential debonding between stitches and laminate. The properties used for the stitch elements were derived from composite micromechanics equations [16], assuming an elastic modulus of 83 GPa for Kevlar rovings.

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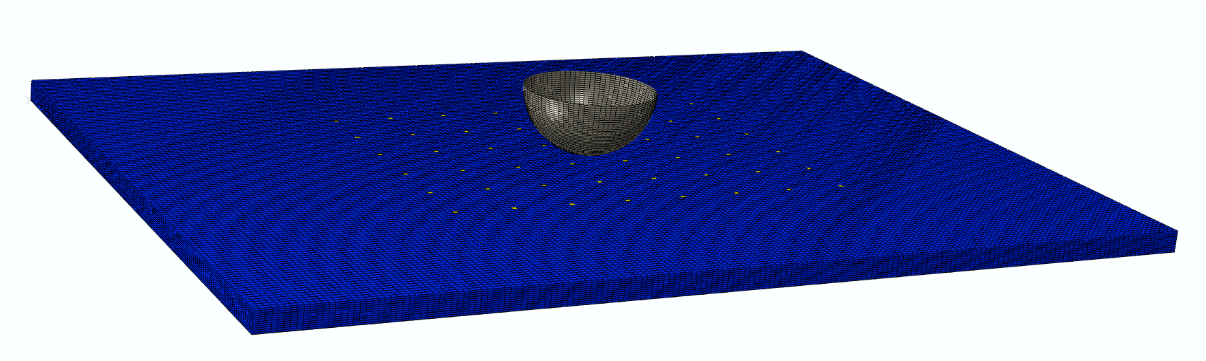

Figure 1. Finite element model of the stitched composite laminate

Table 1: Material properties used in the FE analyses

Layer Properties	E_{11} = 95 GPa; E_{22} = E_{33} = 7.5 GPa; G_{12} = G_{13} = G_{23} = 4.2 GPa $\nu_{12} = \nu_{13} = \nu_{23}$ = 0.261 X_t = 1840 MPa; X_c = -1490 MPa; Y_t = 33 MPa; Y_c = 145 MPa; G_{ft} = 90 (kJ/m^2); G_{fc} = 80 kJ/m^2
Interface Properties	k_N = 120 GPa/mm; $k_S = k_T$ = 43 GPa/mm; N = 30 MPa; S = T = 80 MPa G_{IC} = 520 J/m^2; $G_{IIC} = G_{IIIC}$ = 970 J/m^2

4. Results and discussion

Figure 2 compares experimental force–deflection curves for 3 J and 7 J impacts on $[0_3/90_3]_S$ laminates with those predicted by FE simulations. As visible in the graphs, unstitched and stitched laminates exhibit a similar structural response to impact, characterized by a rather regular rise in load with increasing deflection, without evidence of signal features (sudden load drops, stiffness reductions, high frequency oscillations), usually associated to major fibre fracture events or unstable delamination growth. The plots of Fig. 2 also show that the FE model is able to predict with good accuracy the structural behaviour under impact of both unstitched and stitched laminates. A good agreement is also achieved between experimental results and numerical simulations in terms of damage induced by impact on the laminates. As shown by the damage maps reported in Fig. 3 (impact energy = 7 J), the model is able to correctly predict the size and the global shape of the damage area, as well as of capturing the reduction in delamination size induced by the presence of stitches. The delamination areas predicted by the FE model and measured by X-ray analyes at different impact energies are reported in the graphs of Fig. 4, where it may be seen that stitching only starts to improve the delamination resistance of the laminated for impact energies that are higher than about 3 J or, in other terms, when interlaminar cracks are sufficiently long to fully activate the bridging tractions of stitches across delaminated layers.

This trend is correctly reproduced by the FE model, where the bridging traction forces generated by the stitches are explicitly simulated as a function of the relative displacements occurring between delaminated layers.

Fig. 5 shows numerical and experimental force-displacement curves for dispersed $[0/90]_{3S}$ specimens impacted at two different energies.

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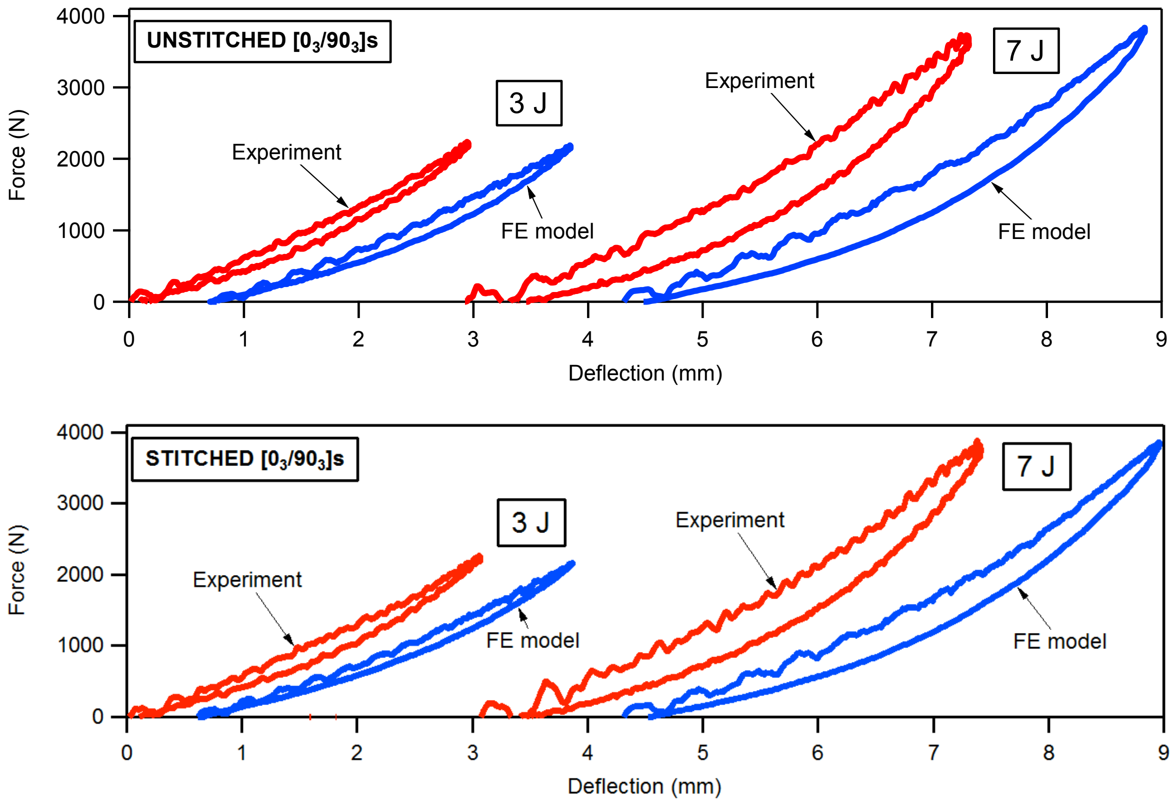

Figure 2. Force-displacement curves of impacted $[0_3/90_3]_S$ samples

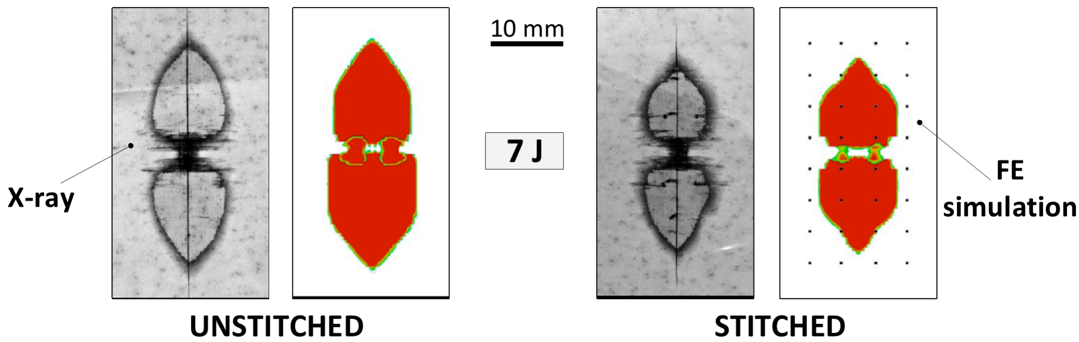

Figure 3. Comparison between projected damage areas as obtained by X-ray and FE simulations in stitched and unstitched $[0_3/90_3]_S$ laminates.

We may see that, similarly to what observed for clustered laminates, stitching does not significantly affect the structural response of $[0/90]_{3S}$ laminates. Unlike clustered samples, however, a sharp load drop in association with some high frequency ringing is visible in the force vs deflection curves of both unstitched and stitched $[0/90]_{3S}$ laminates. X-ray analyses and visual observations of the surface of the samples indicate that initial fibre fracture events occurring around the indentation regions are responsible for these features of the force-deflection curves.

As can be seen in the comparisons of Fig. 5, a good agreement is obtained between FE simulation and experiments for both unstitched and stitched samples. It is seen that the FE simulations capture the general trend of the force-displacement curves and predict the force irregularities induced by the initiation of first fibre damage phenomena. As illustrated by the example of Fig. 6, the FE model is

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also able to succesfully predict the planar extent and the global shape of the delamination pattern developing within the laminate upon impact.

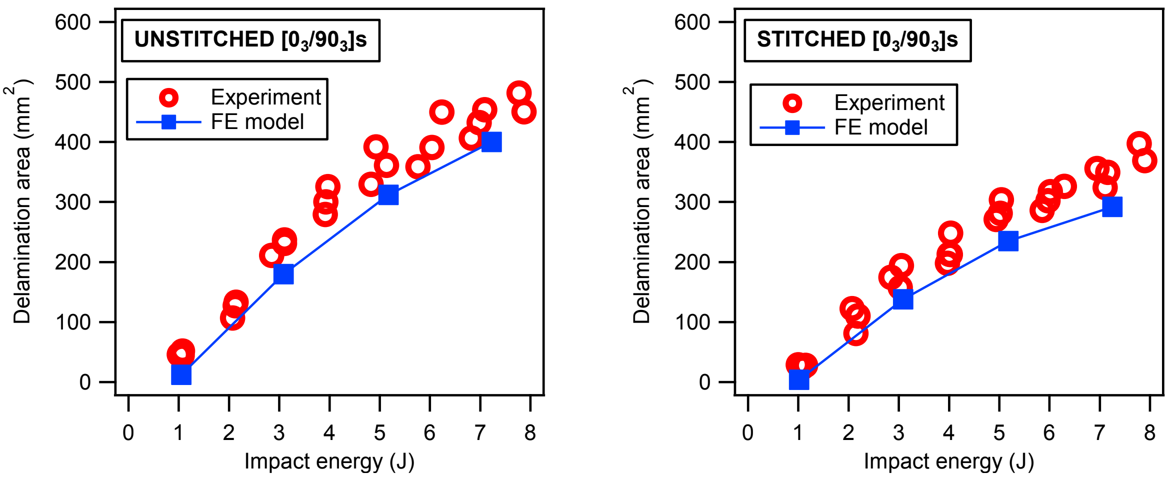

Figure 4. Comparison between predicted and experimental delamination areas for impacts on unstitched and stitched $[0_3/90_3]_S$ laminates.

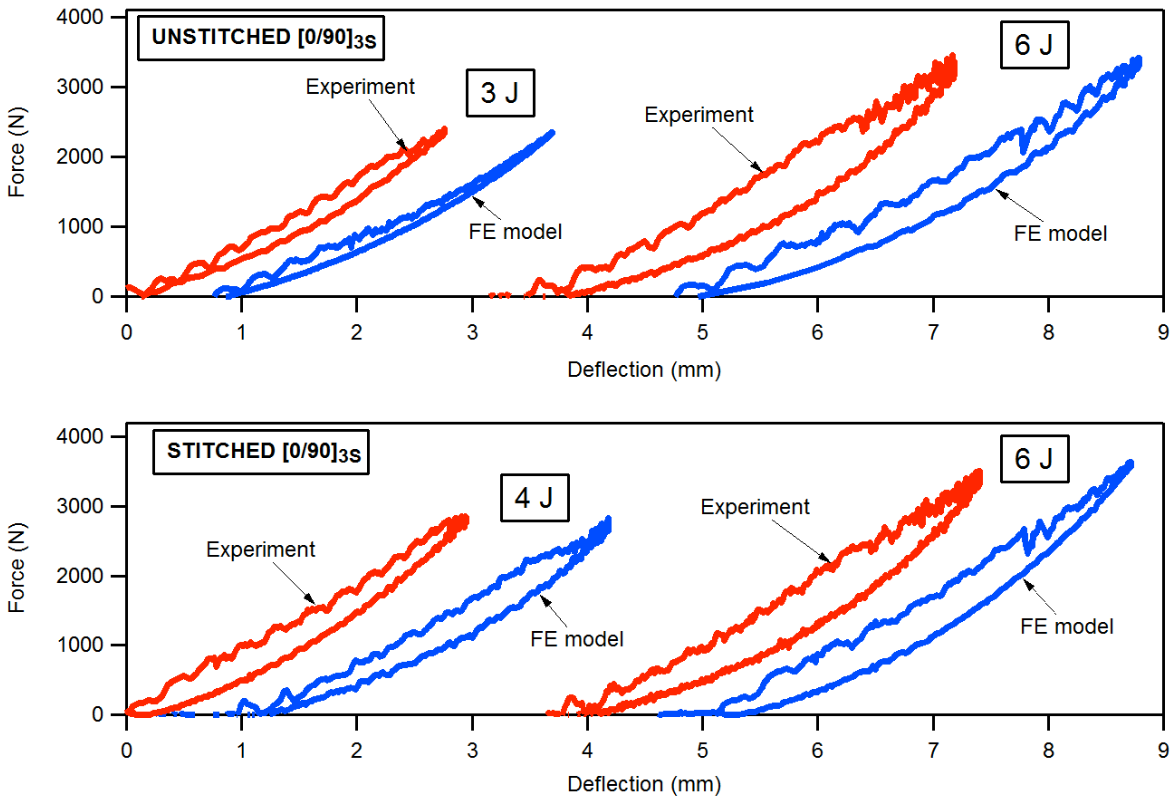

Figure 5. Force-displacement curves of impacted $[0/90]_{3S}$ samples

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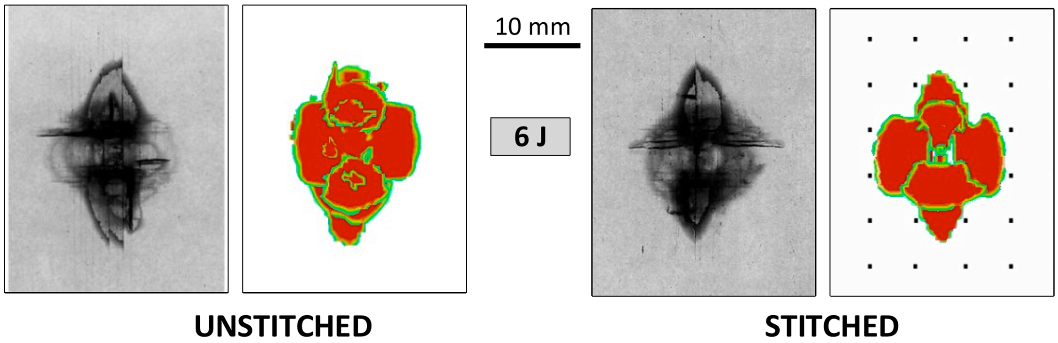

Figure 6. Comparison between projected damage areas as obtained by X-ray and FE simulation in stitched and unstitched $[0/90]_{3S}$ laminates.

The comparison between experimental and numerically predicted projected delamination areas at various impact energies is shown in the plots of Fig. 7.
In contrast to $[0_3/90_3]_S$ laminates, no significant increase in delamination resistance is observed in impacted $[0/90]_{3s}$ laminates upon stitching, as properly predicted by the FE model. The ineffectiveness of stitching in improving the resistance to impact delamination in $[0/90]_{3s}$ samples can be related to the typical damage pattern developing in this class of laminates, which is characterized by small overlapping delaminations as opposed to a single large delamination in $[0_3/90_3]_S$ laminates. As a result of the short length of delaminations, the bridging effect of stitches cannot be effectively activated [17], thus explaining the similar sizes of delaminated areas observed after impact in unstitched and stitched $[0/90]_{3s}$ samples.

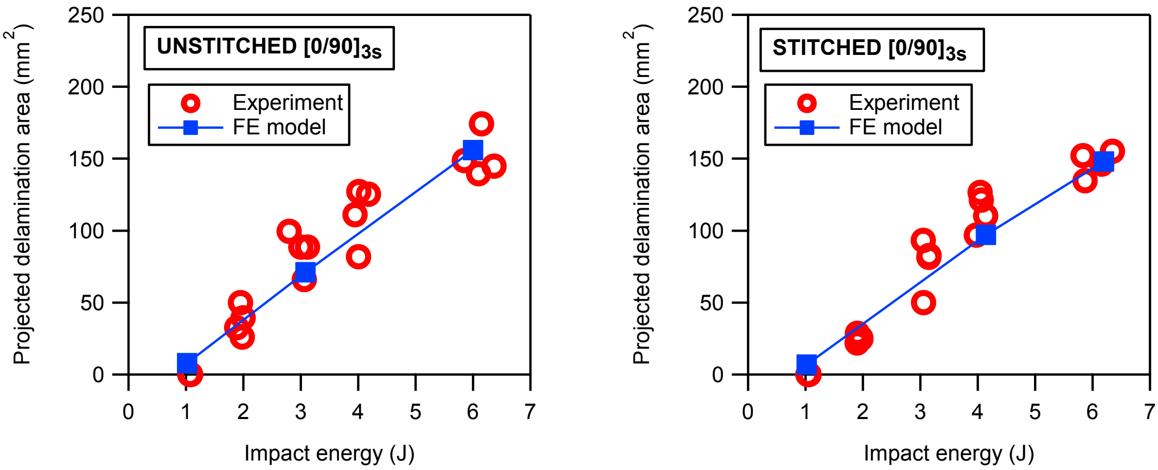

Figure 7. Comparison between predicted and experimental delamination areas for impacts on unstitched and stitched $[0/90]_{3S}$ laminates.

3. Conclusions

FE analyses based on the use of progressive damage constitutive models were used to predict the effect of stitching on the damage resistance of $[0_3/90_3]_s$ and $[0/90]_{3s}$ carbon/epoxy laminates subjected to low-velocity impact. The results of the simulations were compared to experimental data at different impact energy levels in terms of force-deflection curves and delamination areas.
The model correctly reproduced the structural response to impact and the size and shape of the damage areas in both the unstitched and stitched configurations of the two laminate layups.

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The results of the FE analyses indicate that the developed model is able to properly simulate the role of stitches in controlling the delamination resistance under impact and to account for the influence of the laminate lay-up on the efficacy of the through-thickness reinforcement.

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