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STRETCHING THE ENDURANCE BOUNDARY OF COMPOSITE MATERIALS: PUSHING THE PERFORMANCE LIMIT OF COMPOSITE STRUCTURES

Edge impact to composite laminates: experiments and simulations

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Abstract Composite laminates are increasingly being used in more complex structural applications where edges and cut outs are inevitable. These applications include wing skins of military and civil aircraft, further aerospace applications as well as automotive panels and critical structures. Parts of composite structures are particularly vulnerable to impacts, including near the edge of an inspection port or other aperture. Furthermore, impacts to such areas may be to the edge of the laminate rather than the surface. The research described here includes both experimental investigations and finite element simulations of impact damage on the plane of the laminate but near the edge (near-edge), and on the edge (on-edge) of composite laminates. The damage size and mechanisms have been explored. The results demonstrate the vulnerability of composite laminates to on-edge impact.

Introduction

Composite materials are highly susceptible to impact damage and this introduces several design problems. One such problem has been the susceptibility of composite components to impact damage at accidental low-energy impacts which frequently leave no visible mark on the impacted surface but cause considerable internal damage. Critical applications which may be susceptible to such damage include the wing skins of military and civil aircraft and automotive panels [1–3].

Composites response to loads during impact is a complex area of study, both theoretically and experimentally, involving different damage modes including fibre failure, matrix failure and delamination [4]. Investigation of these failure mechanisms has received considerable attention from many researchers over the past two decades. Impact damage can be introduced in various ways to composite laminates in aircraft structures; including during manufacturing processes and by low-velocity impacts in-service caused by tool drop or runway debris. Damage arising from such impact events can considerably reduce the strength and stiffness of structures of composites laminates [2, 3].

Previous work has typically been restricted to the study of normal, transverse impact away from an edge (see Fig. 1). However, in-service impact events are often out-of-plane in nature and such impact events lead to more serious damage compared to normal impact [5, 6]. Such impact damage can lead to more severe delamination, which is difficult or even impossible to detect during visual inspections, and can lead to premature compressive failure of the composite structure [7]. There is very little published work on low-velocity impact on the edge of composite laminates. More recently it has been realised that such edges of composite structures are particularly vulnerable to impacts, including near the edge of an inspection port or other aperture. Furthermore, impacts on the edge of the laminate may lead to more severe damage than impact on the laminate plane [1]. Under low-velocity impact loading conditions the load history can yield

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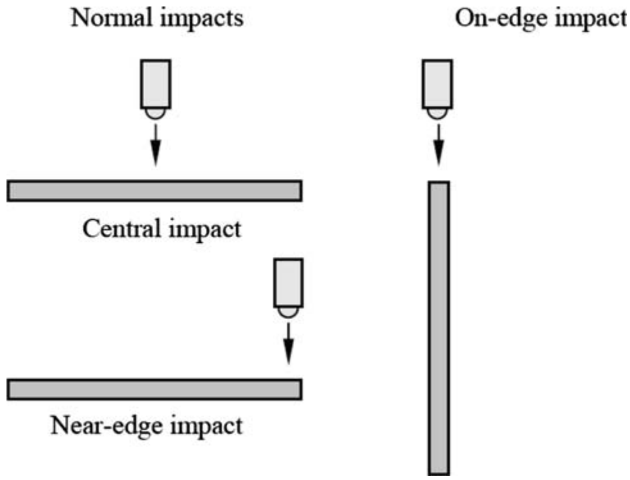

Fig. 1 Descriptions used for different impact conditions

important information concerning damage initiation and growth [8, 9]. The use of composites structures will increase in future if problems regarding impact damage on composites are solved but currently there may be restriction in applications of composites from the lack of understanding of impact damage mechanisms. Understanding of the adverse effect of in-service impact events and impact damage has become critical [3, 6, 10].

The overall aim of this work is to develop an understanding of the way in which accidental damage to the free edge of composite laminates will influence the long-term integrity of a composite structure. This article includes both experimental investigations and finite element simulations of near-edge and on-edge impact to composite laminates. The damage size and failure mechanisms have been investigated.

Experimental method

Materials

The glass fibre reinforced epoxy laminates were prepared in the laboratory using vacuum assisted resin transfer moulding. The quasi-isotropic glass fibre cloth was Cotech EQX 1034 style 3200, non-stitched lay-up. The ply thickness is 0.25 mm. After impregnation of the cloth, the laminates were left to cure at room temperature for 24 h. Finally, the laminates were postcured at 80 °C for 7 h. Two laminate thickness were prepared, 2 and 4 mm, with lay-ups $[0/+45/90/-45]_s$ and $[0/+45/90/-45]_{2s}$, respectively.

Test methods

The impact tests were carried out using a CEATIS Dartvis 6790 drop-weight impact testing machine with computer data acquisition unit DAS4000, which has the capability of 1-MHz sampling rate. The piezoelectric dart striker provides force measurement with respect to time. The velocity of impact is measured using a triggered photocell and the control includes a pneumatic anti-bounce mechanism. The velocity, displacement and incident energy are calculated by the software programme installed in the machine.

The tests were carried out for five different incident energy levels: 1, 2, 3, 4 and 5 J. The impactor mass was constant, 0.740 kg, with variable height and therefore velocity of impact to produce the correct incident energy. The tup radius was 7 mm. The shape of the tup for the near-edge impact was hemispherical. For the on-edge impact, the same tup radius was used, but a rod-shape tup of length 15 mm was used to ensure consistent contact across the edge.

The constraints used for the two types of impact are identical, with the plate being fully constrained around a half-circle window of radius 20 mm. The clamps used and the test arrangements are shown in Fig. 2. All tests were carried out at ambient temperature, between 22 and 24 °C. Three tests were carried out for each condition and excellent reproducibility was obtained. An example of this reproducibility is shown in Fig. 3, which are force/time results for 3-J on-edge impact to a 4-mm laminate. After the impact tests, the damaged area was observed using an optical microscope both in the laminate plane and along the laminate edge. The size of the damaged area in the plane of the laminate has been measured.

Finite element simulations

The finite element simulations have been carried out using ABAQUS Explicit Code, version 6.6. The composite plates are modelled using reduced integration eight-noded brick elements. The plate is modelled at the ply level, with two layers of elements per ply; all finite element results presented here are for 2-mm thick laminate and incident energy of 3 J. A typical mesh for a 2-mm plate contains 24,000 elements. The impactor is modelled as a rigid body, and assigned the mass and velocity values measured in the experiments. The boundary conditions are those imposed in the experiments, with the outside of the half-circle being fully constrained. The impactor is constrained to move in the vertical direction only.

The contact between the impactor and the laminate surface is described using the hard contact definition in Abaqus; it is assumed that there is no friction between the impactor and the plate. Careful selection of the time steps and increments were required to achieve proper convergence. The material properties used for the composite lamina, assuming transverse isotropy, are shown in Table 1. The properties for the different angle plies were

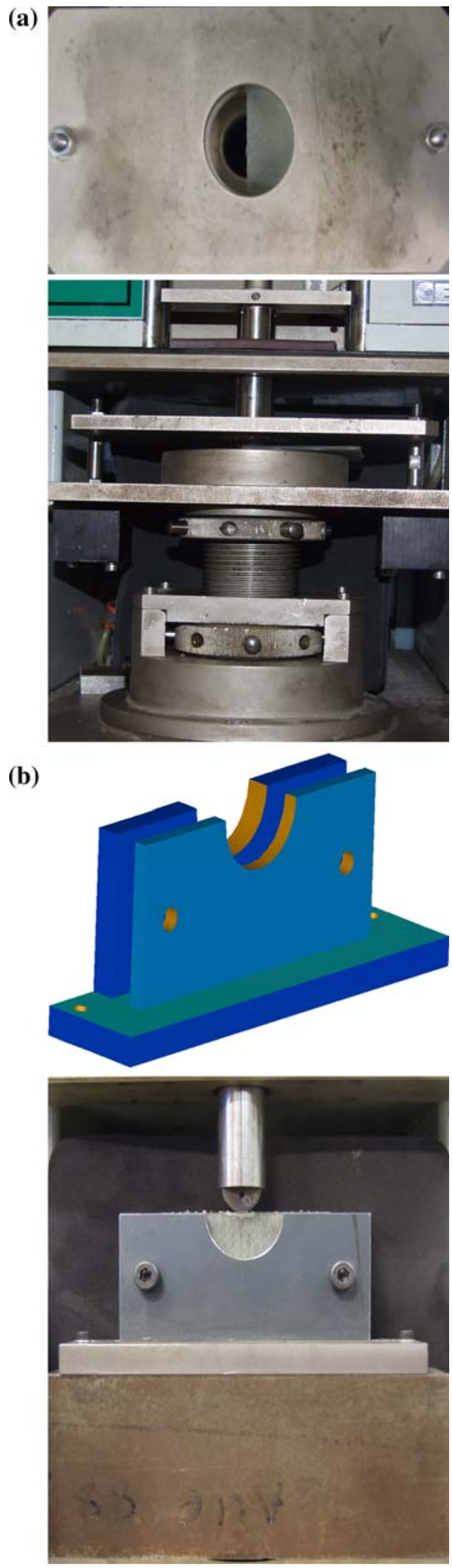

Fig. 2 Impact test clamps and test rigs. (a) Near-edge impact, (b) on-edge impact

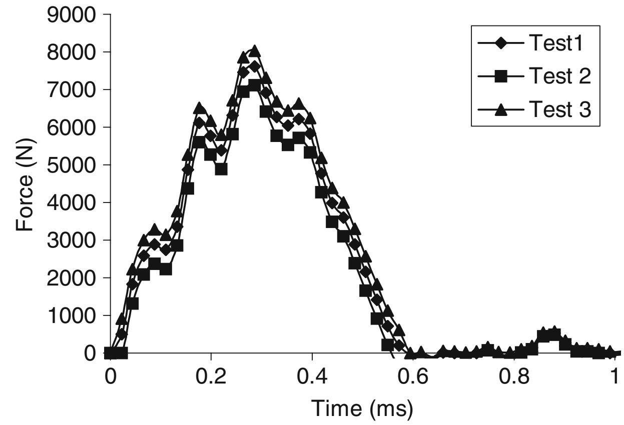

Fig. 3 Comparison of experimental results for identical conditions: force/time traces for 3-J on-edge impact to 4-mm laminate

Table 1 Lamina material properties used for the finite element model

E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	G_{23} (GPa)	v_{12}
43.5	9.5	4.3	3.7	0.28

input using definition of orientation; thus the output directional stresses are with respect to the fibre direction for each ply. In this preliminary model, these properties are elastic, without the inclusion of failure mechanisms. Later models will include failure modelling.

Results

Experimental results

Near-edge impact

The force/time and displacement/time results for the 2- and 4-mm thick laminates subjected to near-edge impact were extracted. The time traces are smooth and show the expected increase in peak force and displacement for increasing incident impact energy. The total impact time also shows a small increase with increasing incident energy. The results for the 4-mm thick laminates showed reduction in impact time and maximum displacement of around 30% compared to the thinner laminate. The peak force measurements for the 2- and 4-mm thick laminates are compared in Fig. 4. The peak force is almost doubled for the thicker laminate; the increase in peak force with incident energy appears higher at lower incident energy.

The values of absorbed energy for the laminates are shown in Fig. 5; the values have been normalised with respect to the incident energy. More energy is absorbed by

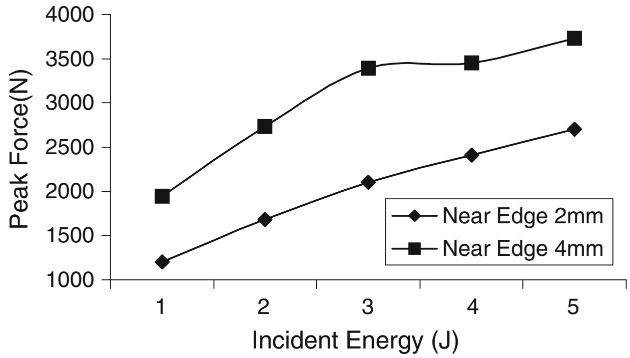

Fig. 4 Variation of peak force with incident energy for near-edge impact on 2- and 4-mm thick plates

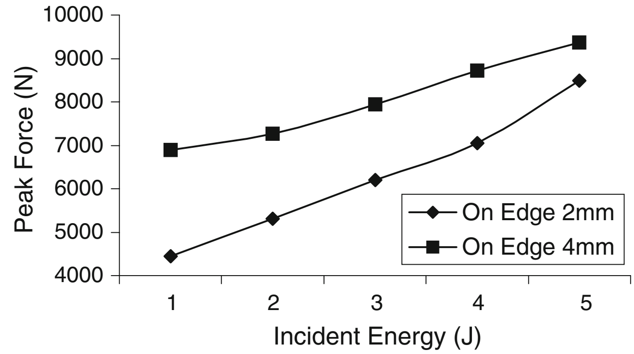

Fig. 6 Variation of peak force with incident energy for on-edge impact on 2- and 4-mm thick plates

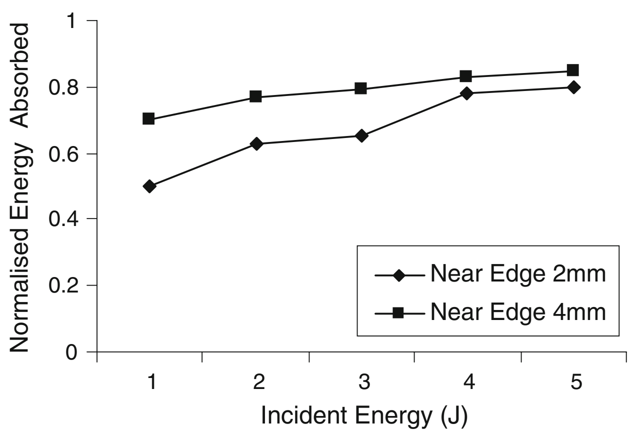

Fig. 5 Variation of normalised absorbed energy with incident energy for near-edge impact on 2- and 4-mm thick plates

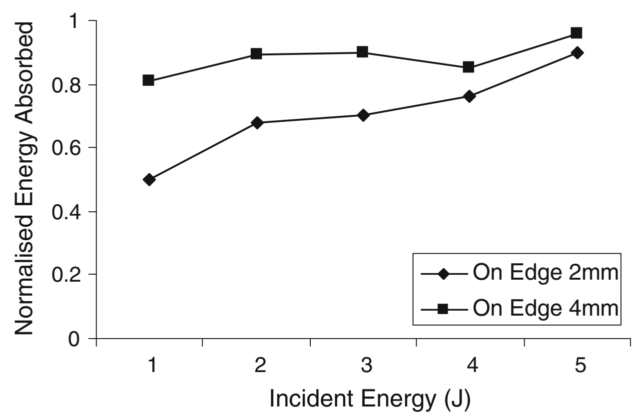

Fig. 7 Variation of normalised absorbed energy with incident energy for on-edge impact on 2- and 4-mm thick plates

the thicker laminate. A higher proportion of the incident energy is absorbed for higher energy impacts.

On-edge impact

The force/time and displacement/time results for the 2- and 4-mm thick laminates subjected to on-edge impact were extracted. In contrast to the near-edge results, the force/time results show distinct vibrations; the displacement results are smooth. The displacement for the 5-J impact shows only small decrease after the maximum value indicating much non-reversible damage. Similar results were obtained for the 4-mm thick laminate. The impact time appears to decrease slightly for the thicker laminate. The peak force measurements for the 2- and 4-mm thick laminates are compared in Fig. 6. The value of peak force is increased for the thicker laminate, but the values appear to converge at higher incident energies.

The normalised values of absorbed energy for the laminates are shown in Fig. 7. In general, a higher proportion of the incident energy is absorbed for higher energy impacts for both laminates. All values are higher than those found for near-edge impact. The 4-mm laminate absorbs very high proportions of the incident energy, approaching nearly all the energy for the 5-J impact.

Observations of damage

The damage in-plane arising from 5-J incident energy impact for both near-edge and on-edge impact are shown in Fig. 8. The measured in-plane values of damage width are shown in Fig. 9. The thinner laminate has higher damage width for both the types of impact. On-edge impact leads to higher damage width. This observation is confirmed by the edge views of the damage for 2-J incident energy, which are shown in Fig. 10. The near-edge impact appears to show a single delamination, but the on-edge impact has multiple, longer delaminations.

Finite element results

These preliminary finite element models do not include the failure mechanisms; the entire impact event has not been captured. The predicted force/time and displacement/time

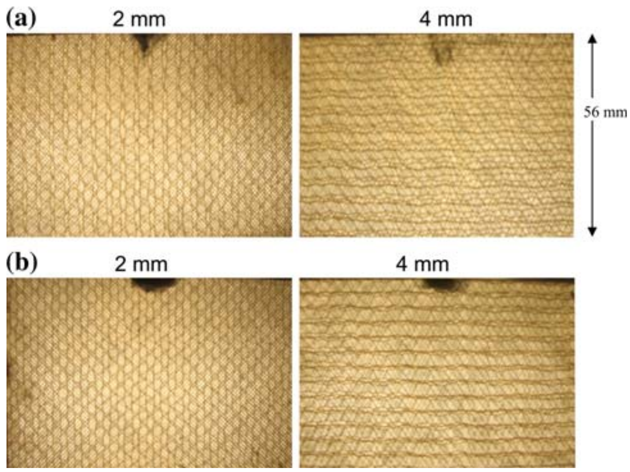

Fig. 8 Plane views of 2- and 4-mm thick laminates showing damage from 5-J impact. (**a**) Near-edge impact, (**b**) on-edge impact

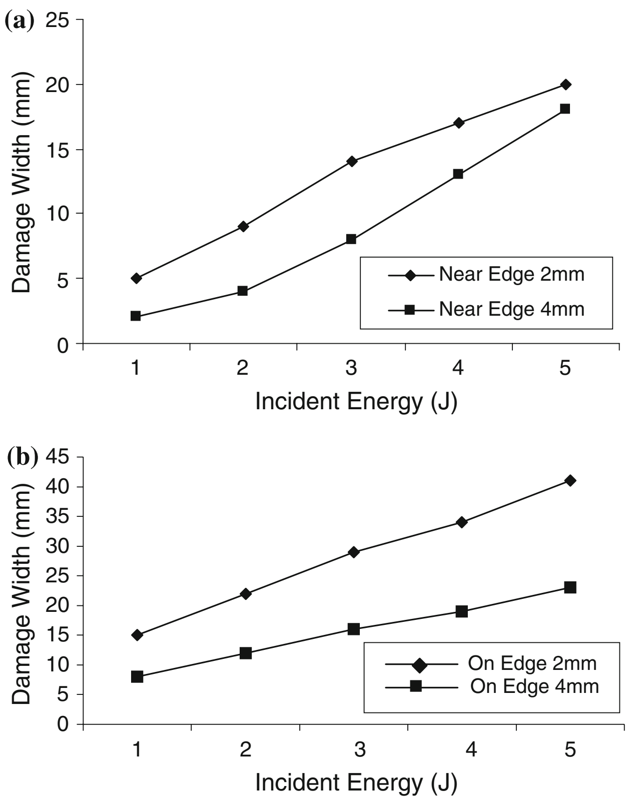

Fig. 9 Variation of measured damage width with incident energy on laminate plane for 2- and 4-mm thick laminates. (**a**) Near-edge impact, (**b**) on-edge impact

results are extracted, and are compared with the experimental results in section "Discussion" (see Figs. 12, 13). As expected for these simulations assuming elastic material properties, displacement and force traces are all smooth and monotonic. Further results from the simulations include stress contours which can be examined to find maximum values for comparisons with the observed failure

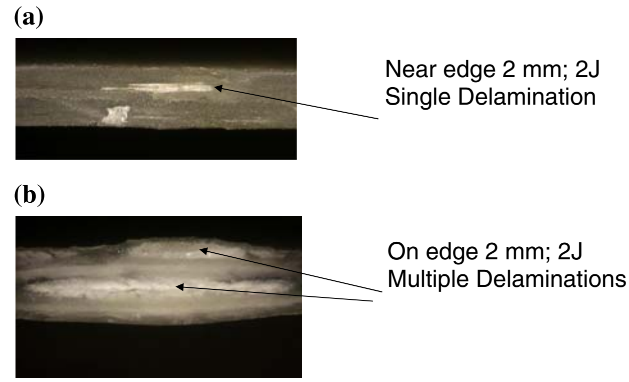

Fig. 10 Edge views of 2-mm thick laminate showing damage from 2-J impact. (**a**) Near-edge impact, (**b**) on-edge impact

failures. As described above, all simulations are for 3-J incident energy impact on the 2-mm thick laminate.

The response of the whole plate to the impact event can be assessed from the in-plane contours of von Mises stress in the top 0° ply. This is the impacted ply for the near-edge impact; for on-edge impact, identical results are found for the opposite, lower, 0° ply. The contours are shown in Fig. 11. Around the impact, the region of high stress is larger for the on-edge impact. High stresses arising from interaction with the boundary conditions at the edge of the plate are found for both the types of impact. For the near-edge impact, these high stresses exist all around the edge; for the on-edge impact they are only found on the edge of the plate below the impact.

The maximum stresses within the individual plies were examined. As described above, the directions of the stresses are all with respect to the fibre direction. For near-edge impact, maximum stress in the fibre direction is found in the lower 90° ply with respect to the impact. For on-edge impact, the maximum fibre stress is found in all the 45° plies. On-edge impact may lead to fibre failure in more plies.

Delamination is expected to arise from transverse fibre stress and shear stress. For both the types of impact, maximum values of transverse fibre stress were found for the 45° plies. For the on-edge impact, maximum shear stress is also found for the 45° plies, but for the near-edge impact maximum shear stress is found for the 0° impacted ply. On-edge impact may lead to more extensive delamination.

Discussion

The experimental results demonstrated the higher stiffness as expected for the on-edge impact. For both the near-edge and on-edge impact, the effects of plate thickness and incident impact energy showed the expected trends. In

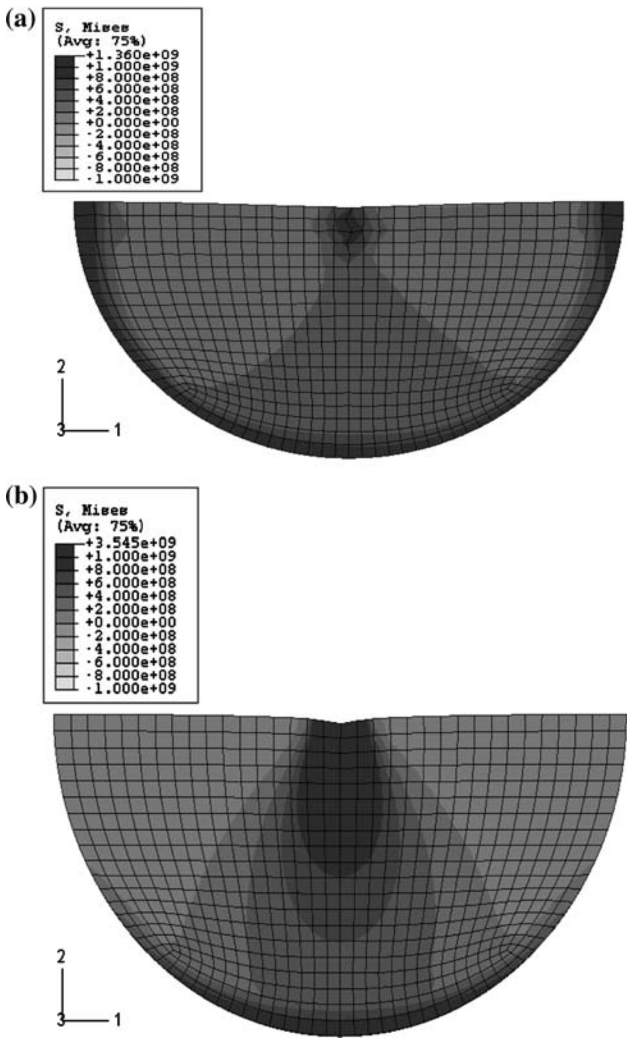

Fig. 11 Predicted contours of von mises stress on the top 0° ply for 3-J impact on 2-mm thick laminate. (**a**) Near-edge impact, (**b**) on-edge impact

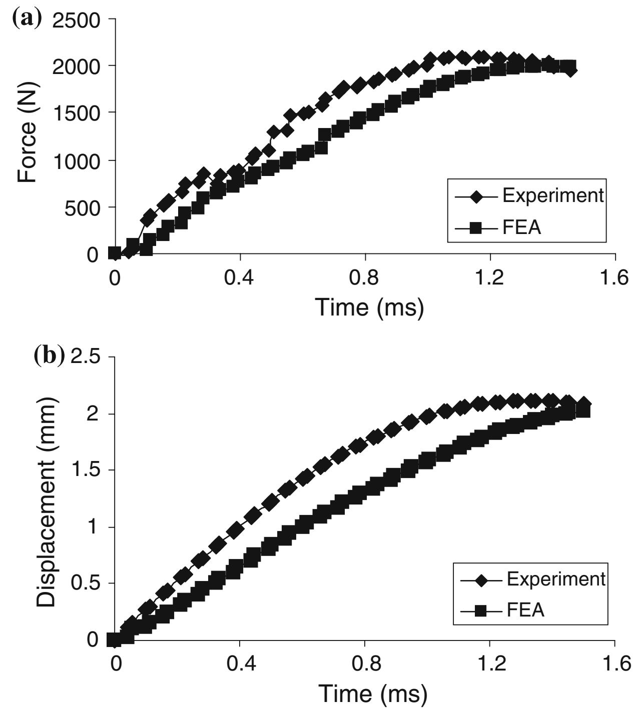

Fig. 12 Comparison of experimental and predicted results for 3-J near-edge impact on 2-mm thick laminate. (**a**) Variation of force with time, (**b**) variation of displacement with time

particular, a higher proportion of energy is absorbed for higher incident energy; it is notable that almost all the energy is absorbed for 5-J impact on 4-mm thick laminate. All experimentally measured force/time and displacement/time traces were smooth with the exception of the force/time results for the on-edge impact (see Fig. 3). We postulate that this may occur from out-of-plane vibration of the specimen, as found in the simulations for on-edge impact, as described below.

The accuracy of the simulations can be explored by comparison of force/time and displacement/time results; the comparisons are made for the impact event, up to maximum force or displacement. Results for near-edge impact are shown in Fig. 12. The near-edge comparisons show very good agreement for the maximum force and displacement. The values of impact event time are in very good agreement. The experimental results initially show higher stiffness than the finite element simulations followed by apparent stiffness reduction, which is expected to arise from failure processes. The finite element results show near linear response as would be expected for these elastic simulations. Results for on-edge impact are shown in Fig. 13. The on-edge comparisons show good agreement for initial stiffness, but the experimental results show decreased stiffness early in the test, as expected from onset of failure processes. The predicted maximum force is about twice the maximum force measured experimentally. The values of displacement are in agreement at the start of the test. The values of impact event time are in good agreement.

These elastic simulations could not be expected to exactly match the experiments. Nevertheless, the validity of our approach has been demonstrated from the good agreement between predicted and measured maximum values of force and displacement, and the very good agreement for the impact time. Examination of the stress contours has indicated that failure processes, including fibre failure and delamination, would be expected to be more severe for on-edge impact; the same comparison was found experimentally.

The simulations can also be used to explain the fluctuations observed in the experimentally recorded force/time traces for on-edge impact. Out-of-plane vibration is clearly visible in this impact simulation. The frequency of the

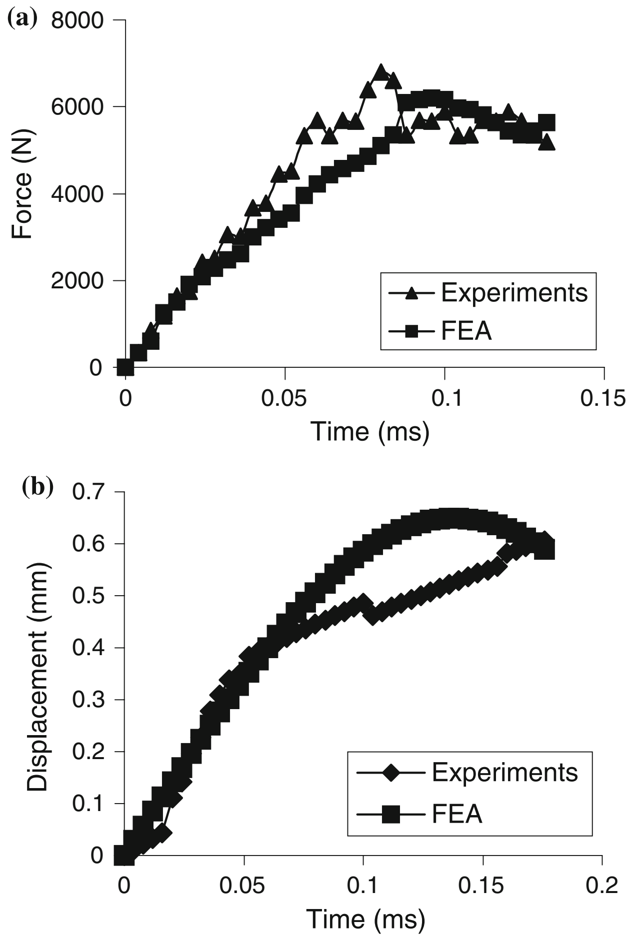

Fig. 13 Comparison of experimental and predicted results for 3-J on-edge impact on 2-mm thick laminate. (**a**) Variation of force with time, (**b**) variation of displacement with time

vibrations is approximately the same as that observed for the fluctuations in the force/time traces. We postulate that such out-of-plane lateral plate vibration is the cause of these fluctuations in load.

These experiments and simulations have been carried out using quasi-isotropic lay-up, with neighbouring plies with relative angle of 45°. This fibre architecture was chosen as the most representative lay-up for many applications. The growth of delaminations is largely controlled by the relative angle between plies, which is 45° for many lay-ups. Thus, although these results cannot be directly related to other composite lay-ups, we propose that the trends found in these experiments and analyses may be relevant. The development of a physical model to describe impact damage, including the effects of near-edge and on-edge impact, is an ambitious but potentially highly valuable future goal of this work. Such development may be possible when the results of the future simulations including the damage mechanisms are examined. If the predicted damage is found to be close to the experimentally observed damage, the information gained from the finite element simulations, including the sequence of damage events, may allow the formation of a physical model to describe the damage.

Concluding remarks

Near-edge and on-edge impact events have been investi-316gated experimentally and simulated using finite element 317analyses. The experimental programme showed the 318expected trends for increased incident energy and laminate 319thickness. Preliminary observations of the damage showed 320the severe nature of the damage arising from on-edge 321impact. The finite element simulations have been shown to 322be valid within their present limitations, and have usefully 323explored the experimental results. The overall results 324highlight the potential threat of on-edge impact; such 325impacts may lead to serious composite failure mechanisms 326including fibre failure and extensive delamination.

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