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# Impact damage to thick carbon fibre reinforced plastic composite laminates

**Charles Breen · Felicity Guild · Martyn Pavier**

**Abstract** Recently, very thick section laminates, up to 20 mm in thickness, have been proposed for the wing skins of large aircraft. Composite components in all aircraft have concerns relating to the presence of accidental damage, but there has been little work to investigate the mechanisms and effects of damage in such thick sections. In this work, carbon fibre composite laminates of up to 12 mm thickness have been subjected to dropped-weight impacts of at most 375 J. Two types of impacts were considered. The first is a central impact where the laminate is completely supported and the second a near edge impact where the laminate is partially supported so that one of its edges is free. The geometry of the damage has been studied using C-scan and deply techniques. The residual strengths of the impact-damaged laminates have been measured in tension and compression. The geometry of damage and level of strength reduction is different for central and edge impacts. Generally, an edge impact causes a greater reduction in compressive strength while a central impact causes more tensile strength reduction.

## Introduction

Recently, very thick section laminates, up to 20 mm in thickness, have been proposed for the wing skins of large aircraft. Composite components in all aircraft have concerns relating to the presence of low velocity accidental damage, but the mechanisms and effects of damage in such thick sections are largely unknown. There are particular issues regarding impact near a free edge, for example the perimeter of an inspection port.

Although most research into impact has been on thin laminates, typically no thicker than 3 mm, a number of recent papers exist that consider impacts to thick laminates [1–6]. Meanwhile, impact of thin fibre reinforced laminates has been extensively studied and reported, for example [7–9]. Very little research exists that considers specifically damage arising from an impact near a free edge, the work of Green, Morrison and Luo [10] being perhaps the most relevant.

In this work, carbon fibre reinforced plastic laminates of up to 12 mm thickness have been subjected to dropped-weight impacts of at most 375 J. The laminates were manufactured by laying up non-crimp fabric (NCF) blankets interspersed with resin film and then autoclaving. An impact of 375 J represents a typical accidental impact, a dropped tool for example, to the wing skin of a large civil aircraft. Two types of impacts were considered. The first is central impact where a plate is clamped between two rings of 200 mm inside diameter and impacted in the centre. The second is near edge impact where the plate is again clamped between the two rings, but so that one edge of the plate is unsupported, and then impacted 25 mm in from the unsupported edge. The results presented from the impact tests are C-scan and deply examinations of the extent of the damage, and post impact residual tensile and compressive strengths of specimens cut from the impacted laminates.

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## Experimental methods

### Laminate preparation

For this work, composite laminates were manufactured using the resin film infusion (RFI) process using Tenax HTS 5131 carbon fibre non-crimped fabric (NCF) plies interspersed with resin film and cured in an auto-clave. Three different types of NCF ply were used. The first type, designated type 7, was a uni-direction blanket while the second type, designated type 2A, was a tri-directional blanket consisting of three separate layers of orientations +45°, 0° and –45° stitched together. The third type, designated type 2B, was again a tri-directional blanket designed to be used opposite to the type 2A blanket to form a symmetric lay-up. Details of the three types of blanket are given in Table 1. The resin film was HexPly M36 epoxy with a mass per unit area of 175 g/m$^2$.

Laminates were produced in three nominal thicknesses: 4 mm, 8 mm and 12 mm. The lay-up sequence of NCF and resin film for a 4 mm laminate is shown in Table 2. For the 8 mm and 12 mm laminates, this same lay-up sequence was repeated as necessary. Once laid-up, the laminate was cured in an auto-clave using the manufacturer's recommended cure cycle. A standard size of laminate of 350 mm by 290 mm was used in this work. The orientation of the laminate was such that the 0° fibre direction was parallel to the longest edges of the laminate.

### Impact of laminates

A falling weight impact machine was used for all the impact tests. The machine has a maximum drop height of 4.5 m and a set of impactors with masses 2.5 kg, 4.6 kg and 8.4 kg. The impactors run in guides so that the point of impact can be controlled accurately. The tip of each impactor is formed of a steel ball with diameter 19 mm.

Laminates to be impacted were clamped between a 10 mm steel top plate and a 30 mm thick steel bottom plate. Both plates were square, 500 mm by 500 mm, and with a central hole of 200 mm diameter. Rather than clamping the laminate directly between the plates, 4 mm thick rubber rings were interspersed between the laminate and the plates.

Two impacts were made to each laminate. The first impact was a near edge impact where the laminate was only partially supported by the clamping plates and the second was a central impact where the laminate was completely supported. Figure 1a shows the clamping arrangement for the edge impact and Fig. 1b the arrangement for a central impact.

Three standard levels of impact were used in the tests by keeping the drop height of 4.5 m constant and using the three different impactor masses. The velocity of the impactor mass was measured just before the impact allowing the actual impact energy for each impact to be evaluated. The variation of impact energy was less that 10% so in the following presentation of results, only the average impact energies of 110 J, 200 J and 375 J are recorded.

### C-scan

After impact the laminates were examined using an ultra-sonic C-scan system with a 2.25 MHz pulse-echo planar transducer to determine the size and location of delaminations. The data acquisition gates were set using

**Table 1** Specification of non-crimp fabric types

| Type | Layer orientations | Mass per unit area (g/m$^2$) | Total mass per unit area (g/m$^2$) | Nominal thickness (mm) |
|---|---|---|---|---|
| 2A | +45° | 267.5 | 642 | 0.6 |
| | 90° | 107 | | |
| | –45° | 267.5 | | |
| 2B | –45° | 267.5 | 642 | 0.6 |
| | 90° | 107 | | |
| | +45° | 267.5 | | |
| 7 | 0° | 321 | 321 | 0.3 |

**Table 2** Laminate lay-up

| | |
|---|---|
| Type 2A (0.6 mm) | 45° |
| | 90° |
| | –45° |
| *Resin* | |
| Type 7 (0.3 mm) | 0° |
| *Resin* | |
| Type 7 (0.3 mm) | 0° |
| *Resin* | |
| Type 2B (0.6 mm) | –45° |
| | 90° |
| | 45° |
| *Resin* | |
| Type 7 (0.3 mm) | 0° |
| *Resin* | |
| Type 7 (0.3 mm) | 0° |
| *Resin* | |
| Type 2A (0.6 mm) | 45° |
| | 90° |
| | –45° |
| *Resin* | |
| Type 7 (0.3 mm) | 0° |
| *Resin* | |
| Type 7 (0.3 mm) | 0° |
| *Resin* | |
| Type 2B (0.6 mm) | –45° |
| | 90° |
| | 45° |

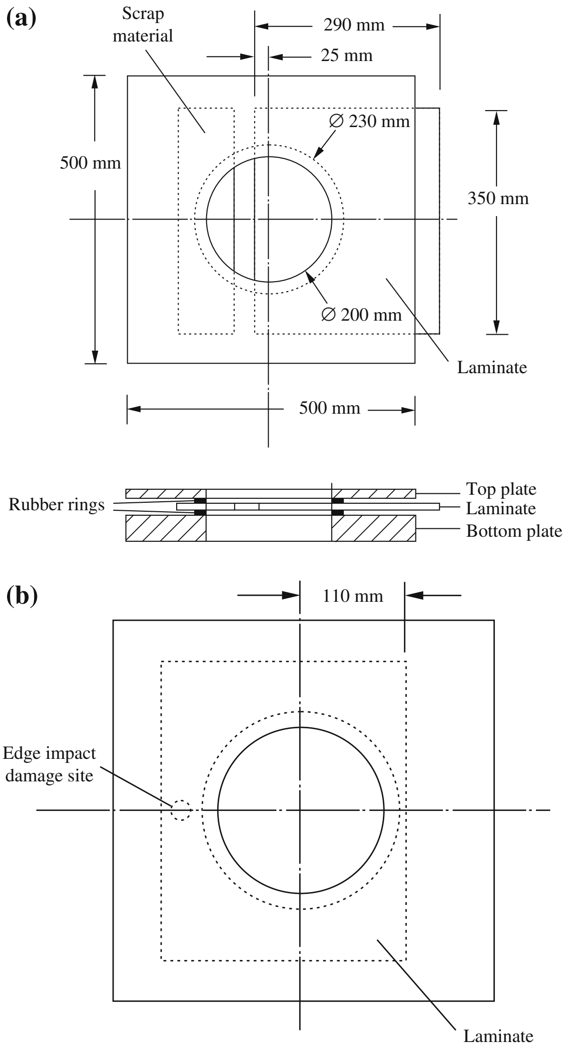

**Fig. 1** Dimensions of the clamping arrangement and the location of the laminate prior to impact for (**a**) edge impacts and (**b**) central impacts

the front face reflection as a trigger and a fixed delay to capture the amplitude and time of flight of the signal reflected from the back face.

## Deply

For one impacted laminate, the fibre cracks through the cross section of the laminate were measured using a deply technique. The method followed is similar to that used in previous research [11] and involved heating the composite to pyrolise the resin in a non-oxidising atmosphere.

First, square coupons of 100 mm by 100 mm were cut from the impacted laminate and the top right corner of each coupon was chamfered to allow easy orientation of the plies after the procedure. Next, the coupon was placed on a set of 8 metal rods 15 mm high in a small open metal tray. The container was filled with argon and placed into an argon filled furnace, pre-heated to 400 °C. After 90 min the furnace was switched-off and allowed to cool over night. Finally the coupon was deplyed by using sheets of clear adhesive film to lift each layer from the coupon one by one. Although the tri-directional NCF blankets used to manufacture the laminate are stitched together, these stitches disappear during the deply process, allowing the individual plies making up the blanket to be separated.

## Post impact strength

Two test specimens were cut from each of the impacted laminates, one specimen centred on the edge impact and the other centred on the central impact. Each specimen was 50 mm wide by 350 mm long. Specimens were tested in tension and compression by clamping them without end tabs in the hydraulic grips of a Mayes 500 kN servo-hydraulic test machine. By experience, a sufficient clamping force was used so that slip just did not occur. The clamped area of the tensile and compressive specimens was slightly different, as shown in Fig. 2. No anti-buckling guide was used for the compression tests.

A number of specimens were cut from an undamaged laminate to find the baseline strength of the laminate. To allow these specimens to be tested in the same machine, a reduced width of 25 mm had to be used.

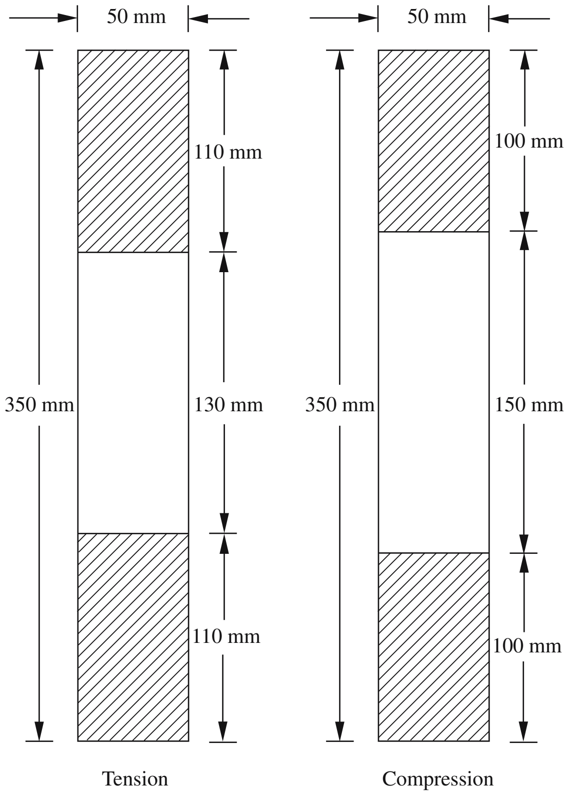

**Fig. 2** Dimensions of tension and compression specimens

## Results

### Damage geometry

Using the C-scan the delaminated area of an 8 mm thick laminate with edge and central impacts of 200 J was measured, as shown in Fig. 3. The figure shows superimposed the location of the 200 mm diameter central hole in the clamping plates for each impact. For each impact, delaminations occurred at multiple interfaces through the thickness of the specimen. Measurements were made of the through the thickness position of the delaminations using a time of flight technique, but these results are not recorded here.

The size of the delaminated area for the edge impact is much larger than for the central impact and reaches beyond the size of the hole in the clamping plates. For each impact, the size of the delaminated area indicates that this delaminated area has been influenced by the size of hole and therefore that a larger hole would give a somewhat larger delaminated area.

The results of the deply measurement of fibre cracks are shown in Fig. 4a for a 200 J edge impact and in Fig. 4b for a 200 J central impact, both to an 8 mm thick laminate. In each case, only the central 60 mm by 40 mm rectangular area of the deplyed coupon is shown. The grid lines in Fig. 4a and b are at 5 mm intervals. Figure 4a and b show the fibre cracks in each group of plies superimposed on each other, but with a symbol at each end of the fibre crack to show which ply the crack appears in. When a fibre crack is shown with only one symbol this means the crack extends beyond the limit of the 60 mm by 40 mm area.

The precise lengths of the fibre cracks in each ply are given in Table 3a and b. Table 3a gives the lengths for the edge impact of Fig. 4a and Table 3b for the central impact of Fig. 4b.

The results shown in Fig. 4a and b, and Table 3a and b show generally that the density of fibre cracks is higher for a central impact than an edge impact, although the lengths of some individual cracks are larger for an edge impact.

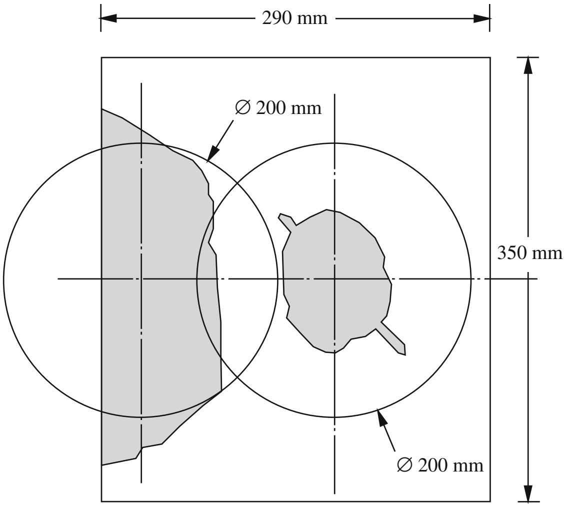

**Fig. 3** Extent of the delaminated regions taken from a C-scan of an 8 mm thick laminate after central and edge impacts of 180 J

### Post impact strength

Results of residual strength measurements versus impact energy for 8 mm thick laminates are shown in Fig. 5a for tensile strength and Fig. 5b for compressive strength. Some measurements were repeated in which case error bars are included to show the spread of results.

Figure 5a shows that in general the residual tensile strength for edge and central impacts is the same, except perhaps for larger impact energies. Earlier work shows that the tensile strength is principally controlled by the loss in cross sectional area of continuous fibres caused by fibre cracks [9].

Figure 5b shows that an edge impact gives a consistently greater reduction in compressive strength than a central impact. The reduction in compressive strength is due to the reduced buckling strength of a laminate that has been divided into a stack of sub-laminates by the presence of a number of extensive delaminations. Observation of the specimens during compressive test showed of the order of 5 delaminations opening as the load increased. It is noted that for the undamaged compressive strength result, buckling occurred before failure and therefore this strength result is not a true measure of the compressive strength of the laminate.

The complete set of residual strength results versus laminate thickness are shown in Fig. 6a and b, Fig. 6a for residual tensile strength and Fig. 6b for residual compressive strength. It was not possible to obtain residual strength values for the 12 mm thick laminate for all impact energies because otherwise the capacity of the test machine would have been exceeded.

## Conclusions

Carbon fibre laminates of 4 mm, 8 mm and 12 mm thickness have been subjected to drop weight impacts up to 375 J. Impacts have been centrally within a supported area of the laminate and also near an unsupported edge. The

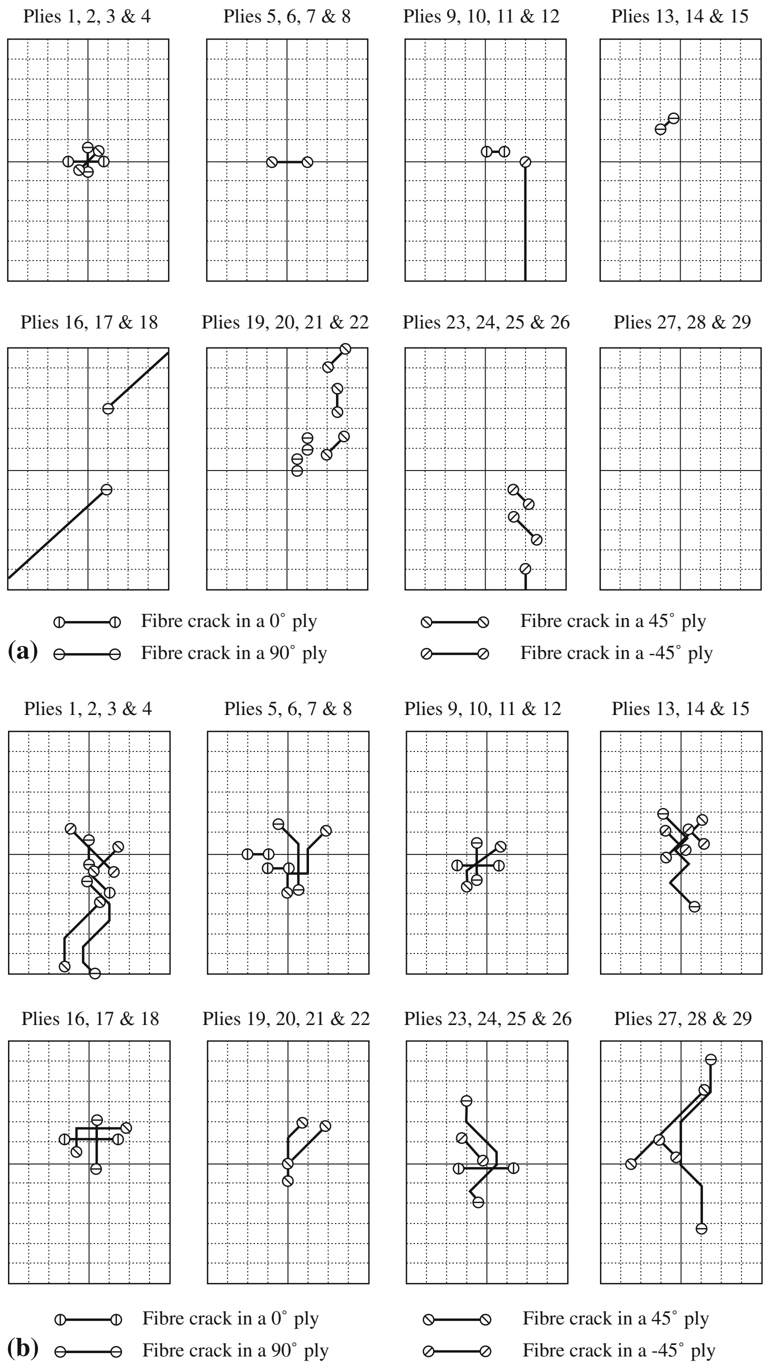

**Fig. 4** Dimensions of fibre cracks in an 8 mm thick laminate after (**a**) edge impact and (**b**) central impact of 180 J

geometry of the damage has been measured using C-scan and deply techniques. The residual tensile and compressive strengths of test specimens cut from the impacted laminates have been evaluated.

Damage resulting from the impacts consists of fibre cracking and delamination. Generally, a near edge impact gives a larger area of delamination and a central impact a greater density of fibre cracks. The size of the damaged areas appears to be influenced by the area of supported laminate.

The residual compressive strength is considerably lower for an edge impact than for a central impact and for each case is much less that the compressive strength of an undamaged laminate. Conversely, the residual tensile strength for a central impact is less than for an edge impact.

**Table 3** Ply by ply fibre crack lengths for an 8 mm thick 200 J (a) edge impacted plate (b) centrally impacted plate

| Ply number | Fibre angle | Nominal thickness (mm) | Fibre crack length (mm) |
|---|---|---|---|
| (a) | | | |
| 1 | –45° | 0.25 | 0 |
| 2 | 90° | 0.1 | 5 |
| 3 | 45° | 0.25 | 4 |
| 4 | 0° | 0.6 | 9 |
| 5 | 45° | 0.25 | 7 |
| 6 | 90° | 0.1 | 0 |
| 7 | –45° | 0.25 | 0 |
| 8 | 0° | 0.6 | 0 |
| 9 | –45° | 0.25 | 35* |
| 10 | 90° | 0.1 | 0 |
| 11 | 45° | 0.25 | 0 |
| 12 | 0° | 0.6 | 4 |
| 13 | 45° | 0.25 | 0 |
| 14 | 90° | 0.1 | 3 |
| 15 | –45° | 0.5 | 0 |
| 16 | 90° | 0.1 | 40* |
| 17 | 45° | 0.25 | 0 |
| 18 | 0° | 0.6 | 0 |
| 19 | 45° | 0.25 | 17 |
| 20 | 90° | 0.1 | 5 |
| 21 | –45° | 0.25 | 1 |
| 22 | 0° | 0.6 | 0 |
| 23 | –45° | 0.25 | 25* |
| 24 | 90° | 0.1 | 0 |
| 25 | 45° | 0.25 | 0 |
| 26 | 0° | 0.6 | 0 |
| 27 | 45° | 0.25 | 0 |
| 28 | 90° | 0.1 | 0 |
| 29 | –45° | 0.25 | 0 |
| (b) | | | |
| 1 | –45° | 0.25 | 13 |
| 2 | 90° | 0.1 | 30 |
| 3 | 45° | 0.25 | 22 |
| 4 | 0° | 0.6 | 11 |
| 5 | 45° | 0.25 | 11 |
| 6 | 90° | 0.1 | 13 |
| 7 | –45° | 0.25 | 2 |
| 8 | 0° | 0.6 | 11 |
| 9 | –45° | 0.25 | 6 |
| 10 | 90° | 0.1 | 8 |
| 11 | 45° | 0.25 | 8 |
| 12 | 0° | 0.6 | 10 |
| 13 | 45° | 0.25 | 8 |
| 14 | 90° | 0.1 | 17 |
| 15 | –45° | 0.5 | 11 |
| 16 | 90° | 0.1 | 11 |
| 17 | 45° | 0.25 | 10 |
| 18 | 0° | 0.6 | 9 |
| 19 | 45° | 0.25 | 13 |
| 20 | 90° | 0.1 | 11 |
| 21 | –45° | 0.25 | 3 |
| 22 | 0° | 0.6 | 0 |
| 23 | –45° | 0.25 | 8 |
| 24 | 90° | 0.1 | 30 |
| 25 | 45° | 0.25 | 0 |
| 26 | 0° | 0.6 | 12 |
| 27 | 45° | 0.25 | 20 |
| 28 | 90° | 0.1 | 33 |
| 29 | –45° | 0.25 | 4 |

The asterix (*) indicates where the crack extends beyond the coupon and hence the crack length is greater than the value quoted

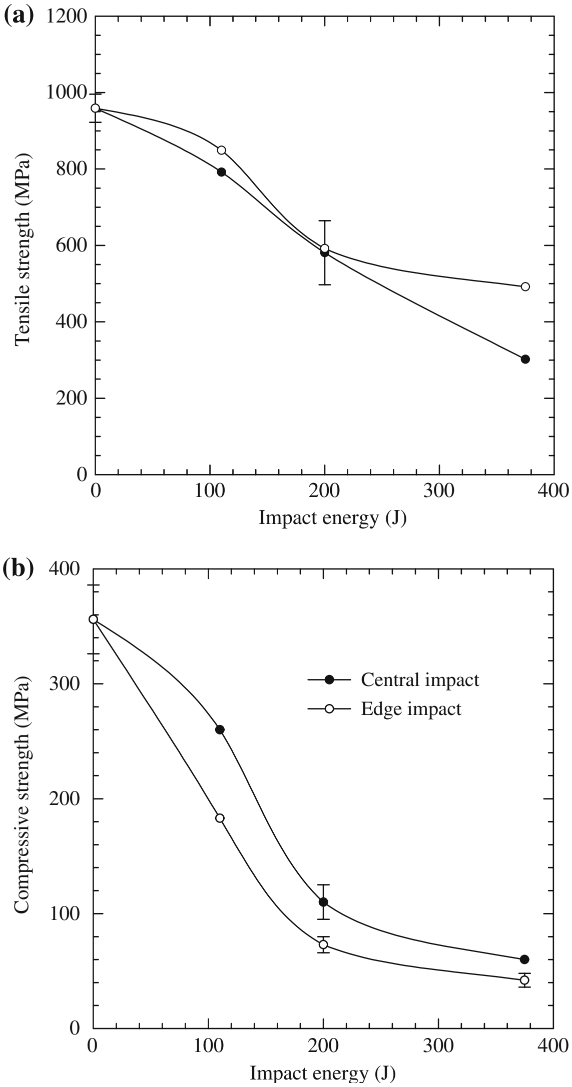

**Fig. 5** Residual (**a**) tensile and (**b**) compressive strength of specimens cut from an 8 mm thick impact damaged laminate versus impact energy

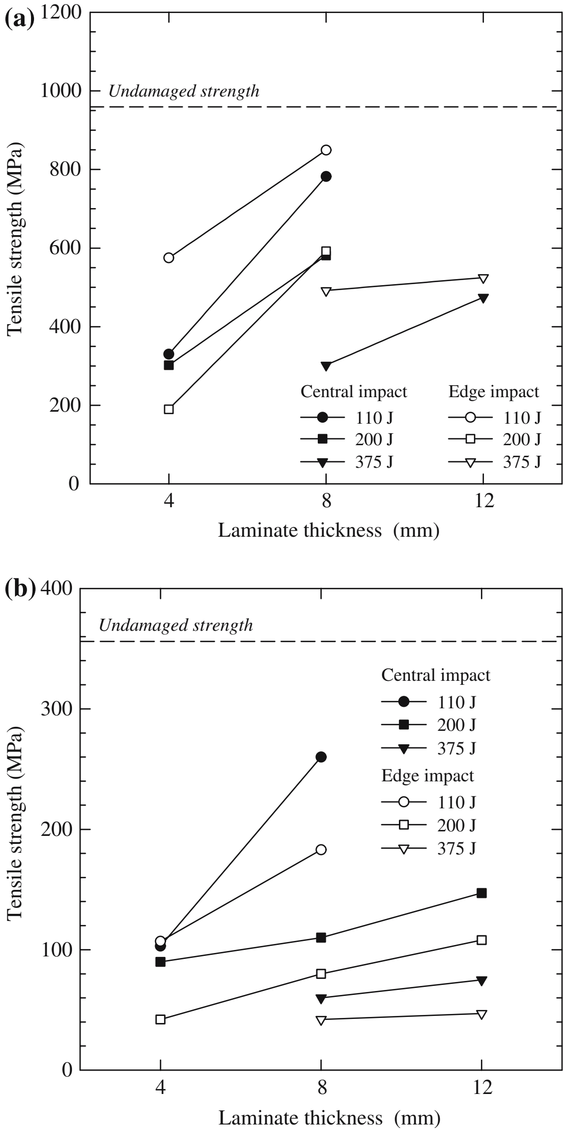

**Fig. 6** Residual (**a**) tensile and (**b**) compressive strength of specimens cut from impact damaged laminates versus laminate thickness

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