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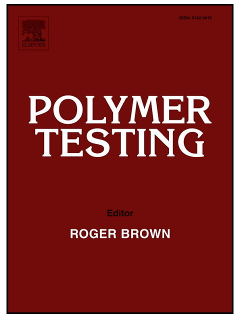

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Material Behaviour

Damage initiation in composite materials under off-centre impact loading

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Abstract

The effect of off-centre impact loading on damage initiation in a woven glass fibre reinforced epoxy resin was studied experimentally. Low velocity impact tests were conducted, in which the incident impact energy was increased until damage was observed in the laminates. It was shown that multiple impacts, with increasing incident energy at the same location, did not greatly influence the critical force for damage initiation, P_{crit}. Subsequent testing on a range of panel sizes showed that the critical force is highest for central impacts, decreasing slowly as the impact location moves towards the boundary. It was also shown that, for off-centre impact loading, P_{crit}, follows a $t^{3/2}$ (t = laminate thickness) relationship that has previously been established for central impact. The slope of the plot of P_{crit} versus $t^{3/2}$ decreases as the impact location moves away from a central location, suggesting that the effective interlaminar shear stress also decreases with increasing offset. Tests at energies well above the damage threshold confirmed that off-centre impact is more serious than central impact loading.

An energy-balance model was used to predict the off-centre impact response of the panels. Agreement between the energy-balance model and the measured impact response was good at energies that did not generate significant damage. Finally, it is suggested that the energy-balance model can also be used to predict a lower bound on the damage threshold energy in composite plates.

Keywords: Composite materials; damage initiation; off-centre impact

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1. Introduction

Composite materials offer a wide range of attractive mechanical properties, such as high specific strength, specific stiffness and excellent fatigue resistance as well as the possibility to tailor properties for a given loading environment. As a result of these advantages, composites are being used extensively in aerospace applications for a wide range of primary and secondary load-bearing components. Unfortunately, these laminated materials are very sensitive to transverse impact loading, which often results in complex failure patterns involving matrix cracking, ply delamination, fibre-matrix debonding and fibre fracture [1–5].

Low velocity impact often results in significant levels of internal delamination within the laminates, as well as matrix cracking and fibre fracture. Although low level damage is not often easily visible to the naked eye, it can lead to catastrophic failure of component under the application of subsequent mechanical loading [4 – 9]. In the past, a large number of experimental and numerical studies have been undertaken to understand and characterise the low velocity impact response of composite structures [5, 10 – 18] with particular attention focusing on damage development in these materials during the dynamic event.

Davies and Zhang [18] investigated the low velocity impact response of a carbon fibre reinforced plastic and presented a strategy for predicting the extent of internal damage within the structure. The authors presented force maps that eliminated the effect of plate size, and noted that there is a sudden increase in damage at a force threshold, with this effect being most pronounced in thicker plates.

Yang *et al*. [19] investigated the influence of projectile diameter, plate dimensions and test temperature on damage initiation in a woven glass fibre reinforced epoxy. They showed that the critical force (P_{crit}) required to initiate damage varied with the indentor diameter. It was also observed that the damage threshold increased with temperature in thinner laminates, but did not exhibit any significant dependency on plate geometry. The influence of varying indentor shape on the damage threshold in thin woven carbon fibre reinforced epoxy was investigated by Mitrevski *et al*. [20] who considered hemispherical, ogival and conical impactors. They showed that the use of a hemispherical indentor resulted in the highest impact force and shortest contact duration of the three impact geometries. Barely visible impact damage was observed following loading by the hemispherical indentor, whereas permanent indentation and perforation occurred following impact by the other indentor shapes.

A number of simple models have been produced to predict the onset of damage (the damage threshold) in impact-loaded composite structures [18, 19, 21, 22]. Schoeppner and Abrate [21] conducted approximately five hundred low velocity impact tests on a number of composite structures to investigate damage initiation in composite plates. They stated that the sudden drop that was observed in load-displacement curves corresponds to delamination development under the point of contact, and showed that the load required to initiate damage increases according to $t^{3/2}$, where t is the target thickness.

Sutherland and Soares [22] developed a simplified shear delamination model to predict the onset of interlaminar fracture in E-glass/polyester marine laminates. They showed that the critical force is related to the interlaminar shear strength through:

$$P_{crit}^2 = \left(\frac{6ILSS^3 \pi^3 t^3}{E} \right) R \qquad (1)$$

where R is the projectile radius, E is the equivalent in-plane modulus and $ILSS$ is the interlaminar shear strength. Here again, the critical force is expected to vary according to $t^{3/2}$.

A review of the literature indicates that few researchers have studied the effect of impact at off-centre locations on the mechanisms of damage initiation and development in composite plates. Breen *et al.* [23] considered the effect of central and near-edge impacts on the residual (tensile and compressive) strength of carbon fibre reinforced plastic laminates. Their results showed that central impact caused a greater loss in tensile strength, whereas edge impacts caused a greater reduction in compressive strength. The impact event of glass fibre reinforced epoxy laminates at edge and near edge locations was investigated by Malhotra et al. [24] . The results showed that these composites demonstrate a high sensitivity to on-edge impact loading. Another work from the same authors [25] showed that on-edge impact of composite laminates leads to severe fibre failure with a small damage area compared to near edge and centre impact locations. Rhead et al. [26] developed a semianalytical fracture mechanics model to predict the compression strength after impact on composite laminates subjected to in-plane free edge impact. The results showed that the predicted values of the strain at which damage propagation occurred have good agreement with the experimental results with error up to 10%. This evidence suggests that the commonly-adopted test scenario in which plates are subjected to a central impact may yield a non-conservative damage outlook. This may have great significance in the aerospace industry, where composite aircraft structures are based on thin skins attached to stringers, spars and ribs. Impact events involving such structures rarely occur at mid-bay locations and consideration should, therefore, be given to more realistic loading conditions.

The aim of this study is to investigate the effect of low velocity impact on the damage initiation threshold in a woven glass fibre reinforced epoxy at off-centre locations. Particular attention is given to investigating the effect of key geometrical parameters, such as the panel size and thickness on damage initiation in the woven laminates. The off-centre impact response of the laminates was modelled using a simple energy-balance approach similar to that used to predict the central impact response of composite laminates.

2. Materials and experimental procedure

The composite material investigated in this research project was based on a plain weave glass fibre fabric in an epoxy matrix (MTM56FRB-GF0100-40%RW). Laminates were manufactured by stacking either 6, 8, 12 or 16 plies of 0.25 mm thick prepreg in a 240 x 240 mm picture frame mould and heating the stack to a temperature of 125 ^{o}C at an approximate heating rate of 5 ^{o}C per minute. The laminates were cured under a pressure of 2 bars (or 0.2 MPa) for 90 minutes, prior to cooling at a rate of 2 ^{o}C/ minute. After manufacture, the resulting panels, with nominal thicknesses of 1.5, 2.0, 2.9 and 3.9 mm, were removed from the mould.

Low velocity impact tests were conducted using the drop-weight tower shown in Figure 1. A steel mass was attached to a carriage with a 12.7 mm diameter hemi-spherical steel indentor. The mass of the impactor was 0.678 kg for all tests. The composite plates were simply-supported on steel rings with internal diameters of 50, 100, 150 and 200 mm. The release height of the carriage was increased to generate energies starting with 0.5 J with an increment of 0.25 J until damage with an approximate diameter of 5 mm was visible in the translucent laminates. Figure 2 shows the set up used in this investigation to detect the initiation of damage. After the damage initiation impact, specimens were removed from the impact tower (Figure 1) and placed at the front of a light ready for imaging. Then, the images were taken by a Panasonic camcorder/camera (HDC-SD90) with a resolution of 2592 x 1944 pixels. The images obtained were analysed using image J (version 1.48v)-public domain software (National Institutes of Health, USA) to measure the damage area. The impact force during testing was measured using a piezo-electric load cell located immediately above the indentor, and the displacement of the carriage was monitored using a high speed video camera. Three samples were tested for each condition and all tests were conducted at an ambient temperature from 18 to 20 ^{o}C.

The elastic stiffness properties of the GFRP laminates were determined by conducting dynamic tests on plates using the aforementioned drop-weight impact rig. The laminates were supported on the same steel rings that were used to determine the damage threshold. The panels were subjected to low incident impact energies (typically one Joule) in order to obtain the initial portion of the load-displacement, P-δ, trace. Following testing, the load-displacement traces were characterized by fitting an expression of the following form to the experimental data, which was confirmed by other researchers [14, 27] .

$$P = K_{b/s}\delta + K_m\delta^3 \qquad (2)$$

where $K_{b/s}$ is the flexural stiffness associated with bending and shear effects, and K_m is the stiffness associated with membrane stretching.

3. Energy-balance model

A simple energy balance model, similar to that employed by Shivakumar *et al*. [27] to predict the impact response of composite laminates subjected to central impact loading, was used to predict the off-centre impact response of the laminates. In their model, it is assumed that the incident energy of the impactor is absorbed by the target in bending, shear, membrane and contact deformations according to:

$$\tfrac{1}{2}mv^2 = E_{b/s} + E_m + E_c \qquad (3)$$

where m is the mass of the impactor, $E_{b/s}$ is the energy absorbed in bending and shear deformations, E_c is the energy absorbed due to contact effects and E_m is the energy absorbed in membrane deformations. In the present study, contact effects were found to be very small with respect to the structure size, and the stiffness value would be largely independent of the contact area, therefore E_c was ignored [28]. By integrating the load-displacement relationship given in Equation (2), the energy-balance model can be written in the form:

$$\tfrac{1}{2}mv^2 = \tfrac{1}{2}K_{b/s}\delta^2 + \tfrac{1}{4}K_m\delta^4 \qquad (4)$$

Using this simple equation, the maximum deflection of the plate (δ_{max}) can be determined for a given impact energy. This value can then be inserted into Equation (2) to yield the maximum impact force, P_{max}, during the impact event.

4. Results and discussion

4.1 Characterisation of the elastic stiffness properties

The initial part of this study focused on the determination of the flexural stiffness properties of the GFRP panels, parameters that were subsequently used in the energy-balance model in order to predict the off-centre impact response of the plates. Figure 3 shows typical load-displacement traces following impact tests at two locations on 8 ply GFRP panels supported on a 150 mm internal diameter ring. Both of the traces are highly oscillatory due to the dynamic nature of the test [29, 30]. They are also non-linear in appearance, with the apparent slope (stiffness) increasing due to membrane stiffening at higher displacements [21]. Offsetting the impact location serves to increase the effective slope of the traces, highlighting the increased stiffness associated with such loading conditions. Equation (2) was then applied to these curves in order to determine the corresponding values of $K_{b/s}$ and K_m. Included in Figure 3 (shown as dotted lines) are the resulting fits yielded by this approach. By applying Equation (2), the effective values of $K_{b/s}$ and K_m were determined for each plate thickness and loading condition, and Table 1 presents the average values (following three tests) of $K_{b/s}$ and K_m that were determined for each test condition. An examination of the table indicates, as expected, that the values of $K_{b/s}$ and K_m increase with plate thickness [30]. It is also evident that both of these stiffness terms increase as the point of loading moves away from the central location. In general, the variations are greatest in the membrane stiffness terms, with the values of K_m becoming very large as the boundary is approached.

Table 1. The average dynamic values of $K_{b/s}$ and K_m for the 6, 8, 12 and 16 ply laminates loaded at central and off-centre impact locations. The inner diameter of the ring support was 150 mm.

x/r	6 ply		8 ply		12 ply		16 ply	
	$K_{b/s}$ [1]	K_m [2]	$K_{b/s}$ [1]	K_m [2]	$K_{b/s}$ [1]	K_m [2]	$K_{b/s}$ [1]	K_m [2]
0.0	40	165	44	200	120	590	200	729
0.2	45	260	49	220	150	620	376	1270
0.4	51	370	80	370	183	1210	578	1379
0.6	61	500	84	540	220	1840	590	2490
0.8	85	2250	97	3300	439	8180	1050	11700

Note: [1] $K_{b/s}$ *10^3 (N/m), [2] K_m*10^7 (N/m^3)

4.2 Damage initiation under low velocity impact loading

In the initial part of the impact study, damage initiation was investigated in the 12 ply (2.9 mm thick) 150 mm diameter panels impacted at a central location and at off-centre positions of 15, 30, 45, and 60 mm. These impact locations correspond to relative positions, x/r, of 0.2, 0.4, 0.6 and 0.8, respectively. Here, the effect of undertaking multiple impacts at the same location was investigated to determine if the number of plates could be kept to a minimum. Figure 4 shows the variation of the critical force, P_{crit}, required to initiate damage in these laminates with the relative location of impact. An examination of the figure indicates that the critical load is higher at the centre of the panel, decreasing to what appears to be a constant value as the support is approached. Interestingly, the value at x/r = 0.8 is approximately twenty percent lower than that at the central location, indicating that off-centre impacts are more serious than the commonly-investigated central impact scenario. Included in the figure are the critical force values associated with a single impact (i.e. on undamaged material). It is clear that multiple impacts have a slightly more deleterious effect than single impacts; however, the differences are very small, suggesting that repeated impacts yield trends that are close to those associated with a single impact event. This is a useful observation, suggesting that it is not necessary to use a large number of panels to achieve an accurate value for the damage threshold force. The evidence presented in Figure 4 indicates that the critical load for damage initiation drops as the impact location moves away from the centre, tending towards a constant value closer to the boundary.

It is well known that composites exhibit a relatively high level of variability and that some degree of scatter should always be expected in the impact behaviour of these materials. Here, the degree of scatter in the damage threshold was assessed by conducting repeat tests on different panels at the same value of x/r. Tests were conducted on 8 ply panels supported on 150 mm internal diameter rings at a location 45 mm (x/r = 0.6) from the panel centre. In each case, the damage threshold force was determined and these values are plotted against test number in Figure 5. An examination of this bar chart indicates that the damage threshold falls within a relatively narrow band, with the critical force varying between 755 and 865 Newtons for these nominally identical tests. Given the well-established batch to batch variability observed in the impact response of most composite materials, such variations are considered acceptable in the current test programme.

The next part of this study focused on investigating the influence of plate geometry on off-centre damage initiation in the GFRP laminates. Here, tests were conducted on eight ply (2.0 mm thick) panels supported on 100, 150 and 200 mm internal diameter steel rings. Figure 6 summarises the critical impact forces for all of the impact locations on these three sizes of panel. It is interesting to note that the data are closely grouped in spite of the fact that there is a relatively large variation in panel sizes. A similar scenario was observed by Yang and Cantwell [19] in which the mass of the targets is not significant in comparison to the impactor mass. Once again, in terms of damage initiation, the central impact condition represents a non-conservative impact case, and cannot therefore be considered as a worst case scenario.

The next stage of this research study investigated the effect of varying the panel thickness for a fixed inner support diameter of 150 mm. Figure 7 shows the variation of the critical force with impact location for the 6 ply (1.5 mm thick), 8 ply (2.0 mm thick), 12 ply (2.9 mm thick), and 16 ply (3.9 mm thick) laminates. As expected, the critical force values increase rapidly with increasing panel thickness. For example, the damage threshold for the 16 ply laminates is almost four times that of the thinnest panel. This can be attributed to the damage initiation mechanism of these panels. Here, damage initiates at the lower surface for the thinnest panel as a result of flexural stress, and at the upper surface for the thick panels due to the locally high contact stress field [31]. Therefore, increasing the target thickness increases the damage threshold with the range of samples investigated in this study.

It is interesting to note that all of the curves exhibit similar trends, with the critical force dropping from a maximum value for a central impact to an almost constant value at locations away from the central location. These trends are also very similar to those observed following tests on the range of 8 ply panels shown in Figure 6.

The data in Figure 7 were analysed in accordance with Equation (1), with the critical force, P_{crit}, being plotted against $t^{3/2}$, where t is the plate thickness. The resulting plot is shown in Figure 8, where the data are plotted for the various values of x/r for all sample thicknesses. An examination of the figure suggests that the data appear to fall on a series of lines, the slope of which decreases with increasing offset ratio. By determining the slope of each of the traces in Figure 8, it is possible to employ Equation (1) in order to calculate an effective value of ILSS. Figure 9 shows the variation of the resulting values of ILSS with offset position, where it is clear that the calculated interlaminar shear strength values decrease as the impact location moves away from the centre of the plate. For example, the calculated value of ILSS for central impact is almost 100 MPa, whereas the value for impact at x/r = 0.8 is equal to approximately 86 MPa. This reduction in the effective ILSS as the panel boundary is approached may be associated with a change in the local stress state, from condition close to pure shear in the centre of the panel to a mixed opening/shear mode local loading condition closer to the support.

4.3 The energy-balance model

The ability of an energy-balance model to predict the off-centre impact response of the panels was investigated by conducting tests on panels at impact energies up to 3.5 Joules. It should be noted that this energy is significantly above the damage threshold for all of the panels. Figure 10 shows the variation of the maximum force with incident energy following offset impacts on 8 ply laminates supported on a 150 mm inner diameter ring. Included in each figure is the prediction offered by the energy-balance model based on the values of $K_{b/s}$ and K_m determined in the previous section. An examination of the figures suggests that the energy-balance model can be used to predict the maximum force for offset impacts with some success, although the predictions of the maximum impact force during impacts at higher energies, where damage is more serious, over-predict the experimental data.

In principle, it should be possible to employ the energy-balance model to predict conservative values for the damage threshold energy in these laminates. Assuming the lowest value for ILSS in Figure 9 (approximately 86 MPa), Sutherland's delamination model shown in Equation (1) can be used to predict the impact force required to initiate damage. The displacement required to generate this force can then be estimated using Equation (2) and this value inserted into Equation (3) to yield the impact energy to initiate damage in the composite. If this is undertaken for the range of laminates considered in this study, the model underestimates the damage threshold by up to 31%, again due to the fact that the most conservative value of ILSS is used.

The final part of this study focused on assessing the influence of off-centre impact loading on damage development in the glass fibre reinforced epoxy. Here, impact tests were undertaken on the 8 ply laminate at locations between x/r = 0 and x/r = 0.8. After impact, the delamination area was measured and plotted against impact energy, and the resulting graph is shown in Figure 11. An examination of the figure shows that damage becomes more severe as the impact location moves from the centre of the panel towards the edge. In many cases, damage at x/r = 0.8 is more than double of that recorded following a central impact. It is also apparent that the severity of damage increases rapidly in passing from low and intermediate values of x/r to the higher value. This evidence suggests that the higher target stiffness at off-centre locations results in high impact forces and significant levels of damage within the target.

5. Conclusions

The effect of off-centre impact on the damage initiation in a woven glass fibre reinforced epoxy was investigated experimentally. Testing showed that the critical impact force for damage initiation is higher at the centre of the panel than at off-centre locations, suggesting that non-central impacts are more serious than the commonly–investigated central impact scenario. In terms of damage initiation, the effect of multiple impacts at the same location was marginally more severe than a single impact, suggesting that it is not necessary to use large numbers of panels to achieve an accurate value for the damage threshold force. For a given target thickness, *t*, the damage initiation threshold does not exhibit any clear dependency on the plate diameter. It was also shown that the critical force, P_{crit}, increases with the sample thickness, loosely obeying a $t^{3/2}$ dependency, similar to that observed in earlier studies following central impact on composite panels. It was shown that for a given impact energy, off-centre loading results in greater levels of damage than central impact, highlighting the severity of this condition. A simple energy-balance model was used to predict the maximum impact force at off-centre locations. This approach can also be used to offer a lower bound on the damage threshold energy for more complex impact scenarios.

Data statement

All data generated through the research work presented in this paper are available.

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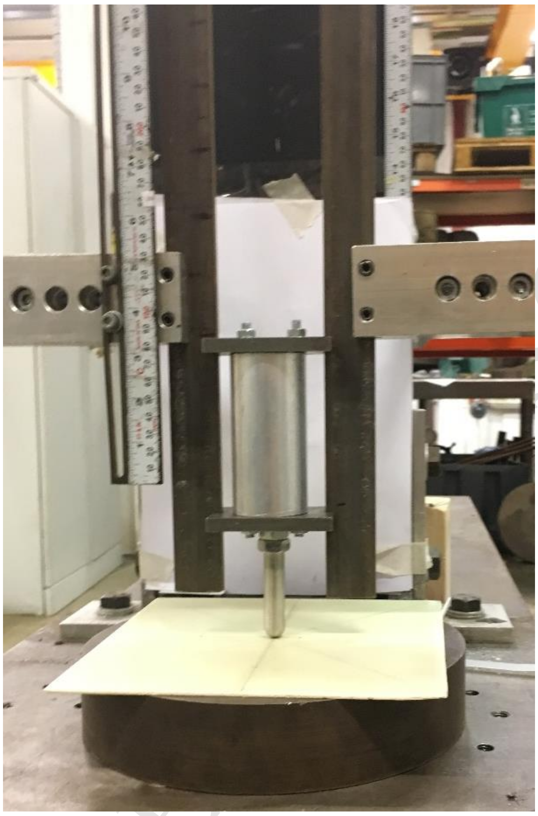


Figure 1. Photograph of the drop-weight impact rig (print in black and white).

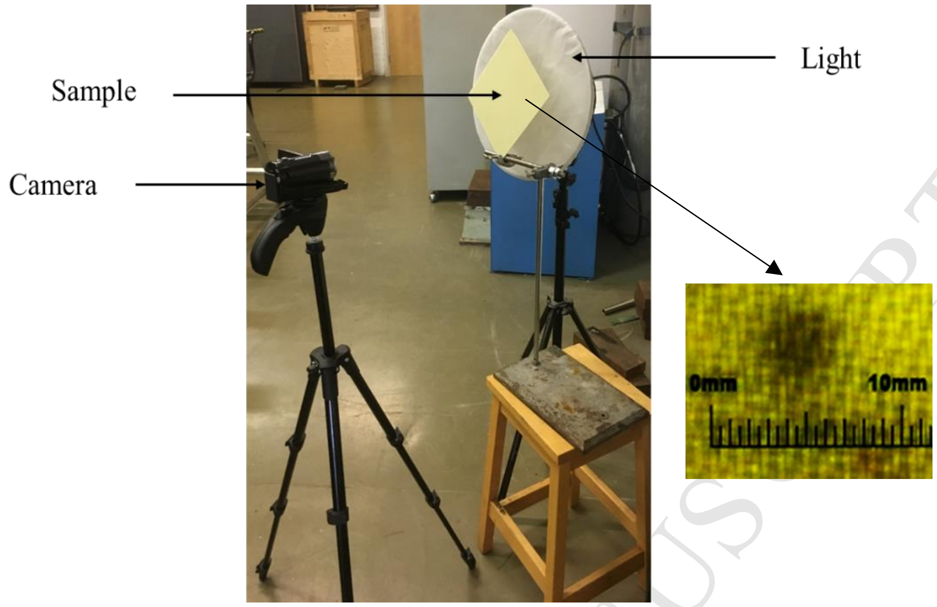


Figure 2. Sample inspection set-up (print in black and white).

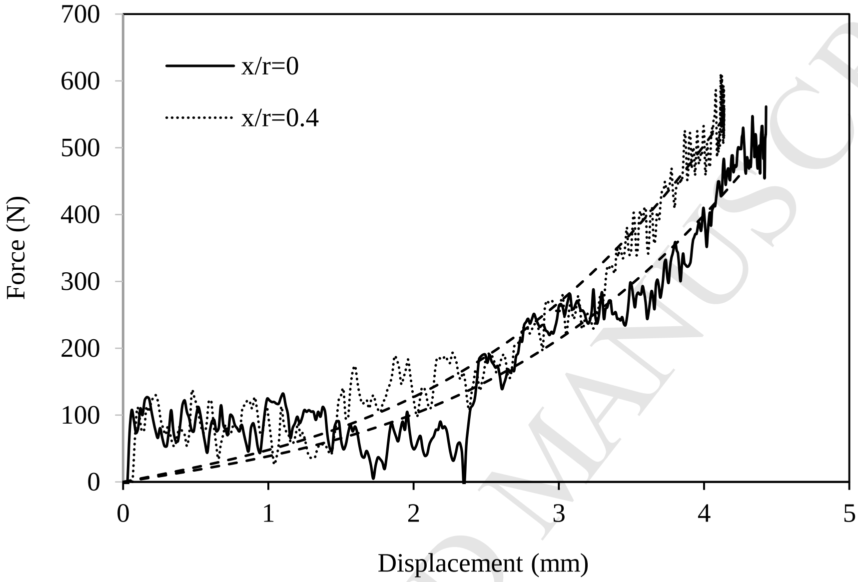


Figure 3. Load-displacement traces following low velocity impact loading at the central (x/r = 0) and a 30 mm (x/r = 0.4) off-centre location of an 8 ply laminate. The inner diameter of the ring support was 150 mm. The dashed lines correspond to curve fits associated with Equation (2).

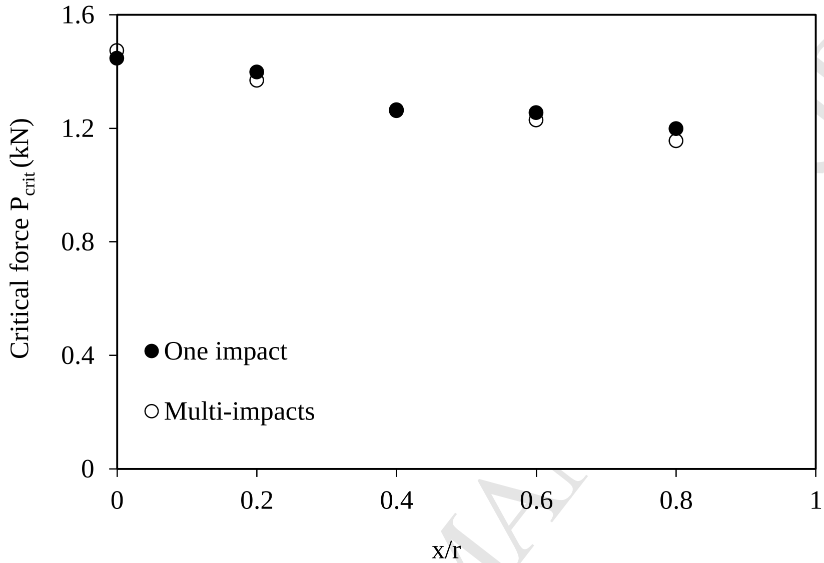


Figure 4. The variation of the critical force, P_{crit}, with relative distance from the plate centre for 12 ply (2.9 mm thick) panels. The inner diameter of the ring support was 150 mm**.** The plot includes values for single impacts and multiple impacts.

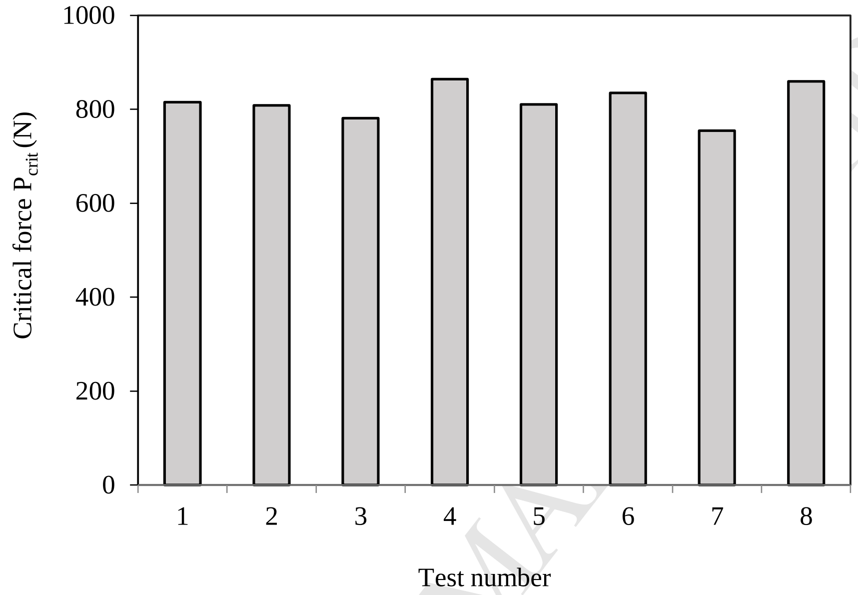


Figure 5. Assessment of the level of scatter in the critical force. Tests were conducted on 8 ply (1.96 mm thick) at an offset distance of 45 mm (x/r = 0.6). The inner diameter of the ring support was 150 mm.

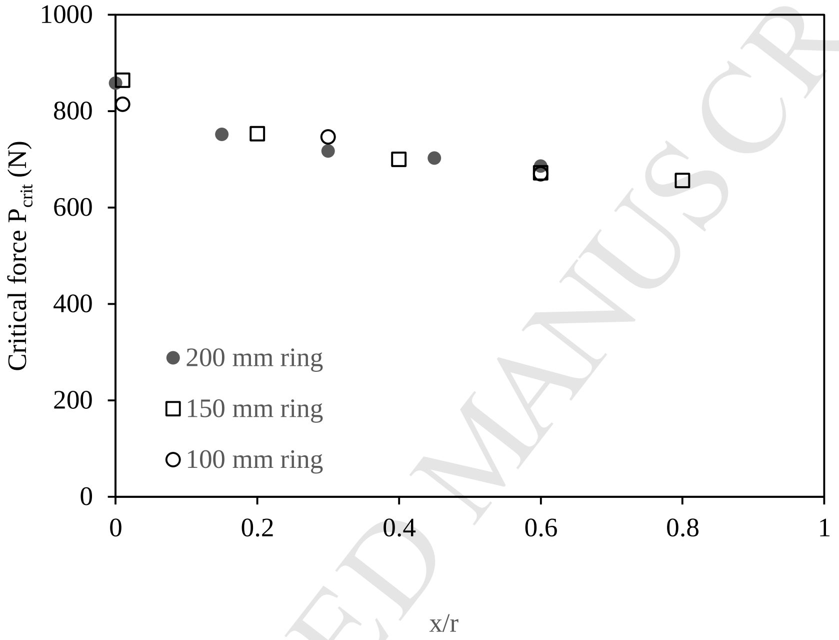


Figure 6. The variation of P_{crit} with x/r for the eight ply (1.96 mm thick) panels supported on rings with internal diameters of 100, 150 and 200 mm.

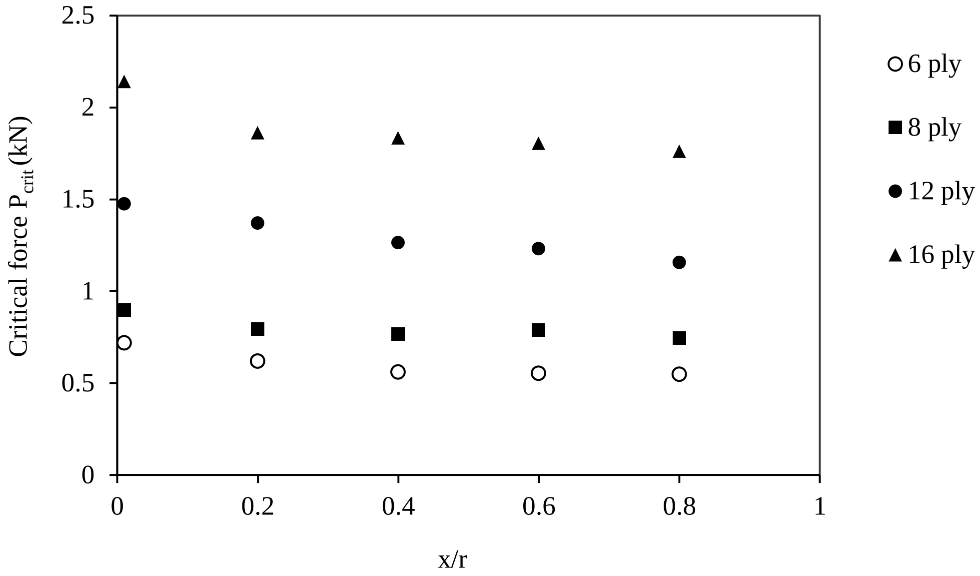


Figure 7. The variation of the critical force with impact location for the 6 ply (1.5 mm thick), 8 ply (2.0 mm thick), 12 ply (2.9 mm thick), and 16 ply (3.9 mm thick) laminates. The inner diameter of the support ring was 150 mm.

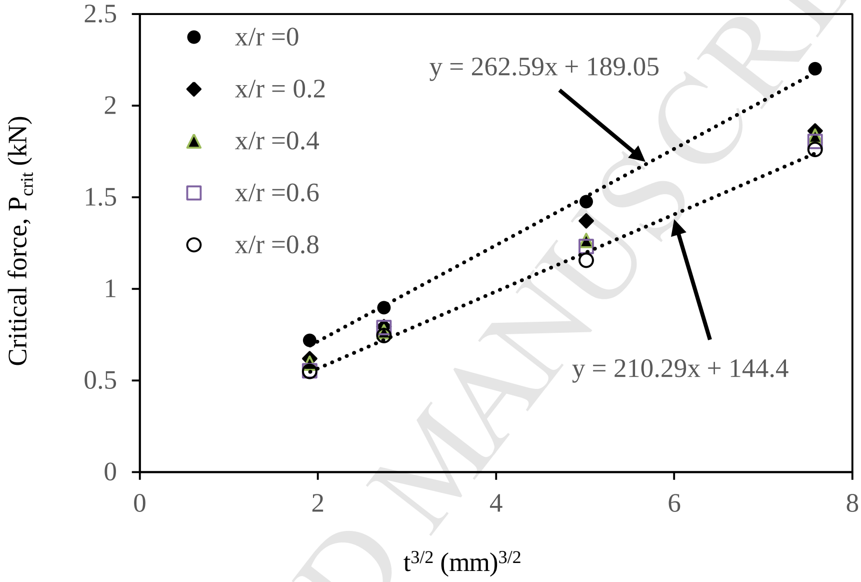


Figure 8. Plot of the square of the critical force, P_c, against $t^{3/2}$ for the data shown in Figure 7. The inner diameter of the support ring was 150 mm.

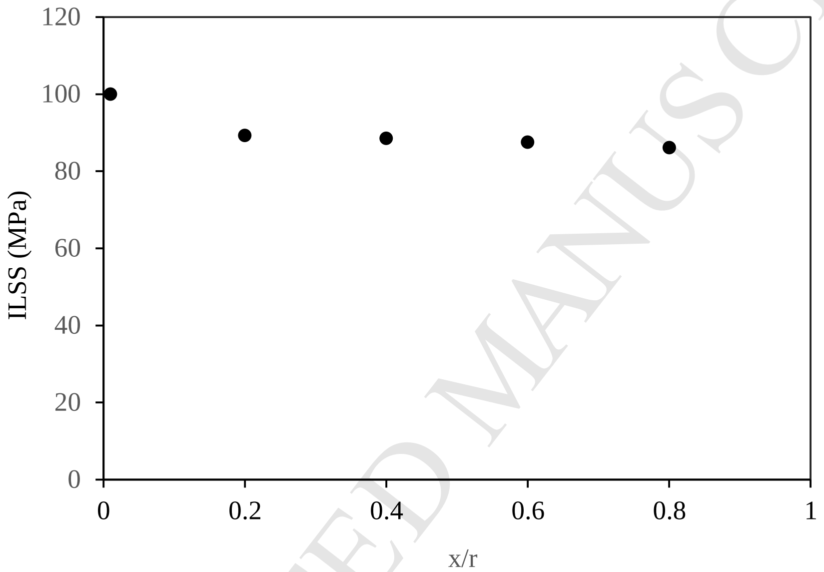
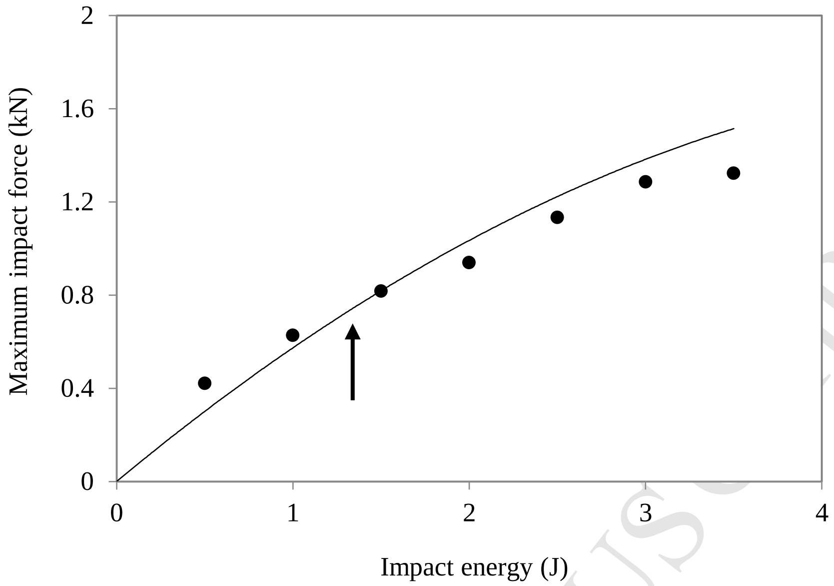
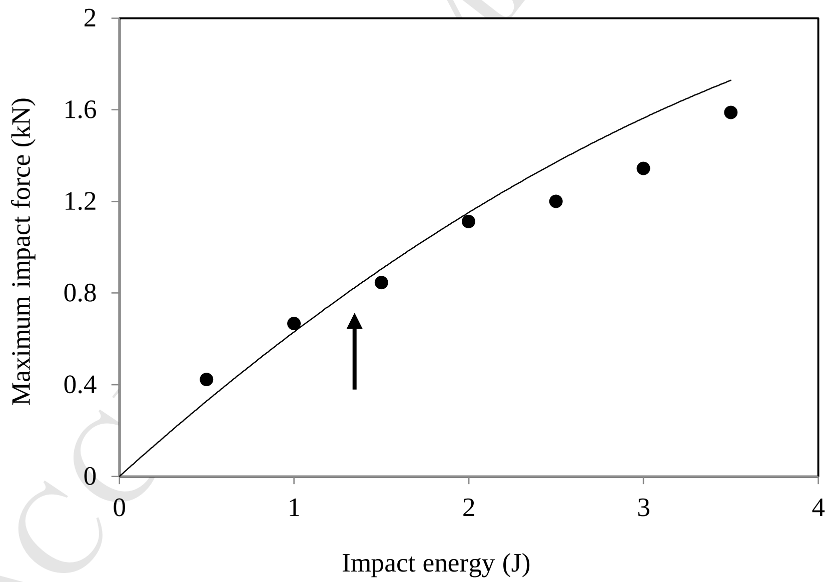


Figure 9. The variation of the values of ILSS with offset ratio, x/r. The values were calculated using the data shown in Figure 8 and Equation (1).



(a) x/r=0.4



(b) x/r=0.6

Figure 10. Comparison of the predictions of the energy-balance model with experimental data for 8 ply (2.0 mm thick) at a) x/r =0.4 , b) x/r =0.6 . The inner diameter of the support ring was 150 mm. The arrows indicate the damage threshold.

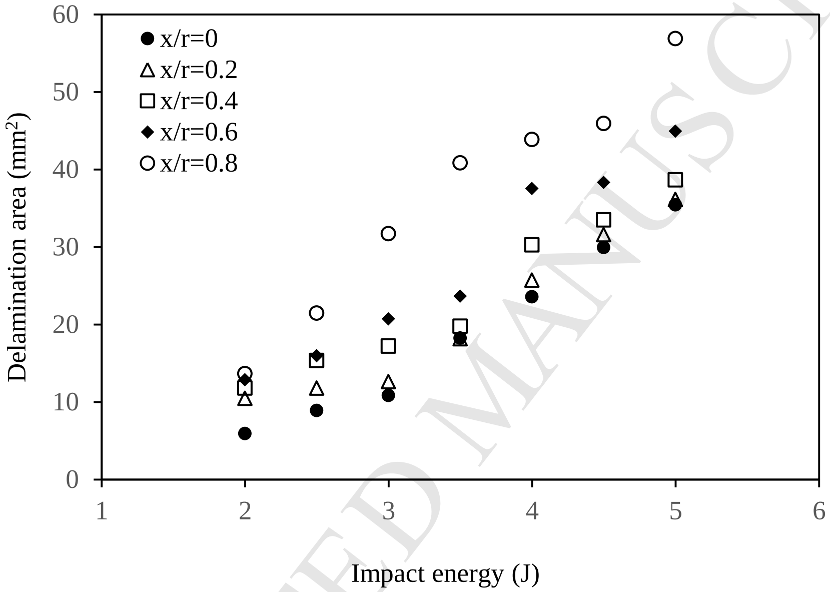


Figure 11. The variation of delamination area with impact energy following impacts at different locations across an 8 ply panel. The inner diameter of the ring support was 150 mm.

Highlights

- The effect of off-centre impact on damage initiation of woven glass fibre composites
- Critical off-centre impact loading follows a thickness$^{3/2}$ relationship same as the central impact
- Off-centre impact is more serious than central impact loading
- Multiple impacts did not greatly influence the critical force for damage initiation
- An energy-balance model is capable of predicting the off-centre impact response of the panels without significant damage