Energy Absorption and Bending Stiffness in CFRP Laminates: The Effect of 45^0 Plies

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Abstract

The impact characteristics of cross-ply and angle-ply composite laminates were investigated, with an instrumented impact drop tester by performing gravity assisted drop tests on $[0/90]_{6s}$ and $[0/45/90]_{4s}$ laminates. The impact energy was kept constant at 12 J for all the tests. From the dynamic responses presented here as force history, energy history and force-displacement plots, relevant characteristics such as contact time, delamination load, absorbed energy, bending stiffness, after impact deflection etc were obtained. The plots were non-smooth, disclosing the salient features of the composites. It was important to note that the $[0/45/90]_{4s}$ was more resistant to impact bending, but incurred more damage as exhibited by its higher contact time and absorbed energy. The laminates were sectioned through the impact point and magnified macro and micro photographs were taken to show the failure modes, which include delamination, matrix cracking etc.

Key words: dynamic loading, bending stiffness, absorbed energy, composite laminates and impact damage.

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1 Introduction

Composite body structures have been used as replacement for metallic ones in several industrial applications, especially in automotive, trains and aerospace industries. Jung-Seok Kim and Seong-Kyun Chung [1] reported that in certain cases to satisfy the design requirements, structures are manufactured with fibre reinforced composite sandwich and metal frames. An attractive aspect amongst others is weight reduction. Considering delicate environmental uses of these materials, damage due to dynamic loads such as debris impact, tool drops, slamming waves, explosion, mine blast etc, is a crucial issue in the research society. The material is susceptible to damage in the through the thickness direction. This damage may not be visible on the surface eg it may be internal delamination.

Since the early 1970s, researchers have been considering various methods for improving the low velocity impact response of composite structures [2-4]. Hybridizing with high modulus fibres has shown improved damage tolerance to low velocity impact and increased the delamination resistance due to bending stiffness mismatch. Stitching is another method to introduce through-the-thickness reinforcement of a laminate. Stitching of laminates prior to curing limits the size of delamination when the composite is subjected to out-of-plane loading and improves its resistance to transverse fracture when subjected to in-plane loading. However, some drawbacks are also present; fibre damage can be introduced by needle penetration during stitching of the fibres and introduction of resin-rich pockets, which cause stress concentrations [3]. These can reduce the strength of the laminate. However, the extra manufacturing step of stitching the laminate to improve delamination resistance can increase the manufacturing cost.

Considering composite materials as a whole, there are many different material options to choose from in the areas of resins, fibres and cores, all with their own unique set of properties such as strength, stiffness, toughness, heat resistance, cost, production rate etc. However, the end properties of a composite part produced from these different materials is not only a function of the individual properties of the resin matrix and fibre (and in sandwich structures, the core as well), but is also a function of the way in which the materials themselves are designed into the part and also the way in which they are processed.

A very obvious decision required of a designer of composites is judgement between the stacking sequence, bending stiffness and damage resistance. In this study fibre reinforced laminates of stacking sequences $[0/90]_{6s}$ and $[0/45/90]_{4s}$ were impacted with a standard instrumented drop weight facility from a height of 40 mm with a nominal impacted energy calculated to be 12 J; to evaluate the failure mechanisms and characteristics of the laminates. Taking cognizance of labour, it is cheaper to manufacture the cross-ply laminates compared to the angle-ply composites. The 45^0 plies improve the torsional stiffness of the laminate and absorb shear loads. An issue of interest here are the effects of the angle plies on the impact characteristics of the composite.

This paper was prompted as a preliminary study to evaluate the dynamic response of composite laminates which can be used for duct covers to replace metallic ones at the Scottish Exhibition and Conference Centre (SECC). The metallic ones are too heavy to be lifted by one person. The light choice is a sandwich composite, with fibre reinforced laminated skins. SECC will be satisfied with duct covers that can withstand 10 tonnes load without failure. There are duct covers in use elsewhere which can withstand loads as high as 40 tonnes [5].

2 Materials

The prepregs used for this study were manufactured by Hexcel® and the material code is HexPly®913; a unidirectional carbon-fibre epoxy lamina, having 60% fibre volume fraction and a lamina thickness of 0.125 mm. The cured [at 125^0C] matrix properties as obtained from Hexcel® are shown in *Table 1*

Table 1 Cured matrix properties

Tensile strength	65.5 MPa
Tensile modulus	3.39 GPa
Cured density	1.23 g/cm^3

The carbon fibres in the prepregs were manufacture to Hexcel aerospace specification and/or their industrial grade standard. Typical fibre properties are as shown in *Table 2*.

Table 2 Typical fibre properties

Tensile strength	4.80 GPa
Tensile modulus	276 GPa
Ultimate elongation	1.74%
Carbon content	94%
Density	1.78 g/cm^3

3 Fabrication of specimens

The roll of carbon fibre reinforced prepreg lamina was cut with a blade, 45^0 square and straight ruler to laminae of sizes 150mm x 150mm. Hand lay-up techniques were applied to stack, the plies obtaining the following configuration:

- $[0/90]_{6s}$
- $[0/45/90]_{4s}$

These laminates were cured in the autoclave [*Fig 1*] using the manufactures recommended cure cycle for the product. The composites were then cut with an Edwards Guillotine into bits of sizes 75mm x 75mm for drop test.

The major components of the assembly include vacuum bagging, sealant tape, breather cloth, release films and aluminium plates. The vacuum generated was maintained throughout the curing period. The autoclave was opened slightly, for the specimens to gradually cool to room temperature, before the vacuum pressure was released

The release films were carefully placed at the bottom and top of the samples ensuring little or no wrinkles would be generated when the vacuum was applied. Wrinkles of the films may affect the surface finish of the specimens. Typically, bagging of samples in the autoclave is as shown in *Fig. 2*.

Fig. 1 The autoclave

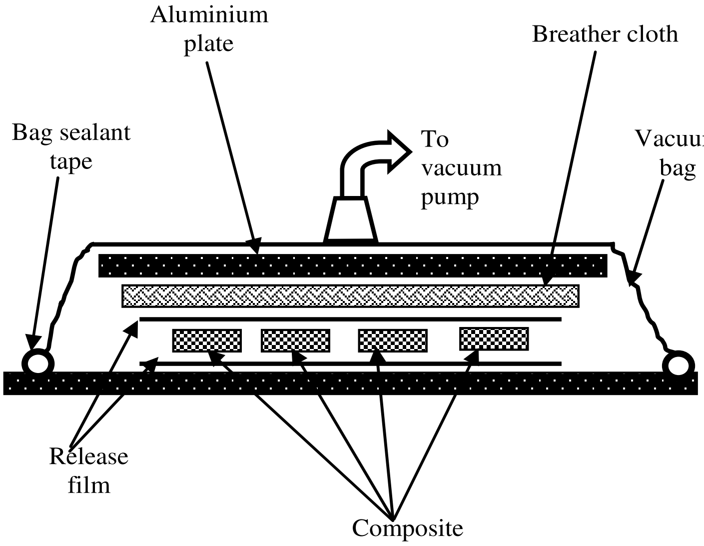

Fig. 2 Schematic arrangement of bagged composite samples under vacuum pressure in the autoclave.

4 Impact test

In an impact event, energy is absorbed by a material through elastic deformation, plastic deformation and through the creation of new surfaces by failure mechanisms. In the case of composite materials there is very little or no plastic deformation. The composite laminate is brittle; it comprises of carbon fibres, as reinforcement and thermosetting epoxy resin as matrix and exhibits, little or no plastic flow before fracture.

A photograph of the instrumented drop impact striker is shown in *Fig 3* and *Fig 4* is the schematic of the same. During the impact, the resistive force exerted by the sample on the striker is measured as a function of time and stored for subsequent display and analysis. That is the force transducer detects the contact forces at many consecutive instants and transient data are recorded for each sample tested, which includes time, energy, velocity and deflection. The fracture event lasts, typically for a few thousandths of a second.

The system calculates the corresponding velocity history of the impactor by integrating the force history (after being divided by the mass of impactor) with the use of initial impact velocity. Similarly, the corresponding displacement history of the impactor is calculated from integrating the velocity history. Based on the force and displacement histories of the impactor, the energy history, which represented the history of energy transferred from the impactor to the composite, is also calculated.

Fig. 3 Photograph of the ROSAND instrumented drop tester.

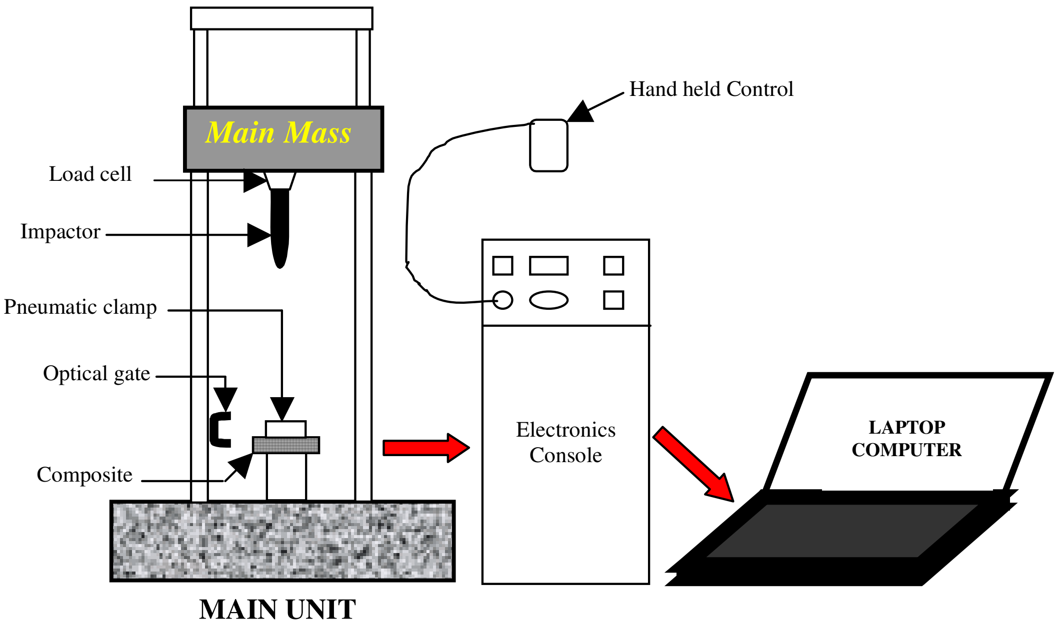

Fig. 4 Schematic of the ROSAND impact tester

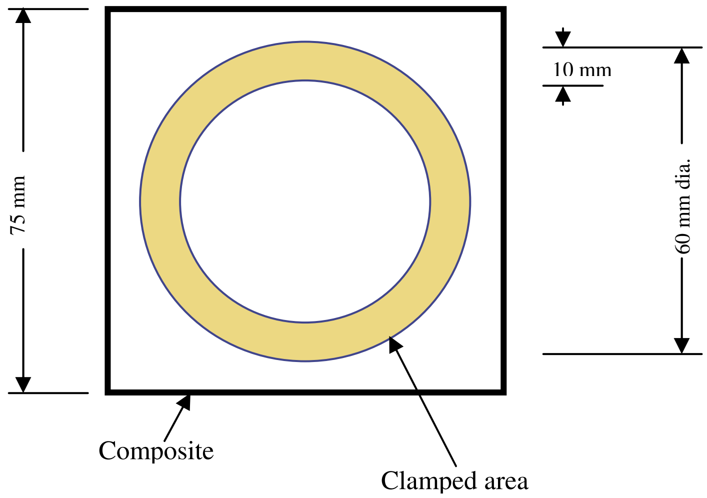

Fig. 5 Dimensions of the composite plate and the clamped area.

Table 3 Drop test conditions

S/n	Description	Specification
1	Impactor mass	30kg
2	Impact nose	Hemispherical
3	Diameter of impactor	12.1mm
4	Boundary condition	Clamped
5	Drop conditions	Gravity assisted free fall
6	Drop height	0.04 m

The summary of the test conditions are shown in *Table 3* and *Fig 5* shows a schematic of the clamped composite panel. The sweep time of the drop tester is very important as it sets the data acquisition speed. In order to preserve as much accuracy as possible for the test, it was set to 50 microseconds per data point. To ensure confidence of the data five low energy drop test were performed on aluminum plates. The drop height was 0.02m and the impact energy calculated to be 5.9J, as the drop mass was 30kg. A representative plot of this response is shown in *Fig. 6* and the peak loads from the results were 11.3kN, 11.8kN, 11.8kN, 11.6kN and 11.8kN. That is an average of 11.66kN and standard deviation of 0.2 or an estimated standard machine error of 1.7%.

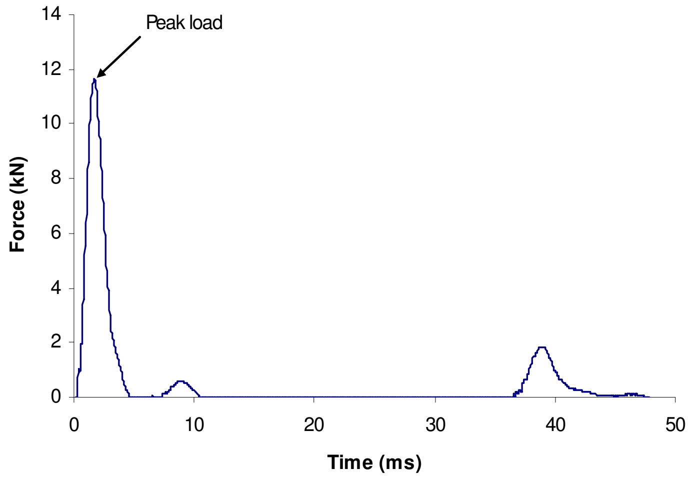

Fig. 6 A representative impact response of an isotropic material [aluminium].

5 Test Method

For this investigation an instrumented *ROSAND* impact test system, type 5, Model MOM40, was used. The equipment is capable of striking samples at energies of up to 580 J. It has a fixed mass of 30 kg and the impact can only be varied by changing the drop height. Composites samples, in this study were all impacted from a drop height of 0.04m, ie impact energy of 12 J. A pneumatic clamping fixture with a 60 mm external diameter ring, secured the composite plate with a pressure of 8 bar. The samples were impacted with a 12.1 mm diameter impactor with a hemispherical tip, fabricated out of high strength steel. The test was performed twice for each sample configuration and the results were very identical.

Physical examination of the tested composites showed indentation and splitting of the bottom ply from the impact direction. Also the specimens were sectioned through the impact zone, the cut surface ground with 800, 1200 and 2400 grit silicon carbide papers with water; and macro photographs obtained at x10 magnification, with Sony digital still camera DKC-CM30.

The micro-structural photos were taken with a Nikon Epihot metallurgical microscope at x 50 magnification. In preparing of samples for these photos, they were (in addition to being sectioning through the impact point of the composite with an abrasive cutting disc and cooling water) mounted on

Struers Durofix-2 cold mounting acrylic resin [*Fig. 7*]. Then ground with 220grit Sic paper with cooling water at 300rpm, followed with 800, 1200, 2400 grit papers to reduce scratch pattern. Finally, they were polished with 3 micron diamond suspension with DP blue lubricant on DP-Dur polishing pad at 150rpm.

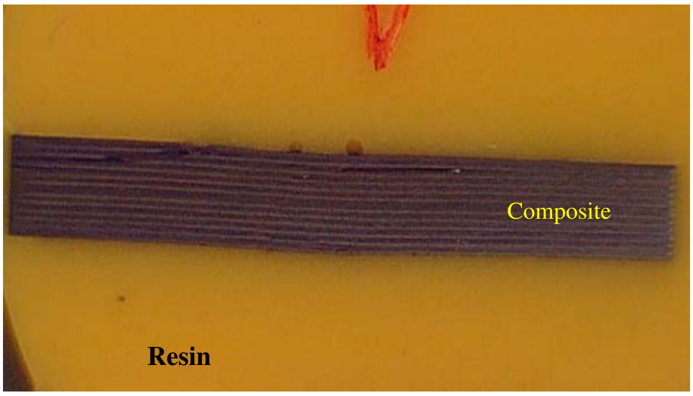

Fig. 7 Sectioned composite mounted on resin for micro-photograph.

6 Test results

The effect of the impact is to cause an indentation and a finite radius of curvature in the contact zone. The representative plots of load and energy against time and load-displacement responses for the composite samples are displayed in *Figs 8 to 11* illustrating the salient features of the behaviour. Although the magnitude of the impact is the same different stress waves propagate through the composite because the configurations are different. The differences in load history pattern can the attributed to the presence of the 45^0 layer in the angle ply laminate. The force – displacement curves for the laminates reach a maximum and returns to the abscissa.

The curve rises is a stick-slip manner till a point of sudden fall in load is reached which is defined as the threshold of damage. After this, the distances between opposite consecutive peaks of the plot keep reducing towards the ultimate load. Internal delamination is due to the transverse shear stresses (or strain) and the threshold is associated with a sudden load drop indicating dramatic stiffness reduction and a significant damage event [6]. Delamination appears as a form of separation of adjoining plies. The random frequency response after the threshold of damage is an indication of the interaction of the many damage mechanisms of the composite.

The thresholds of the Hertzian failure are different for the laminate configurations implying that each composite has it own unique load-bearing ability. Although there may be some cracking of the matrix, locally around the impact point, it is after the threshold of damage that the impact energy is dissipated; before then the energy is stored in the load bearing component, ie the fibres.

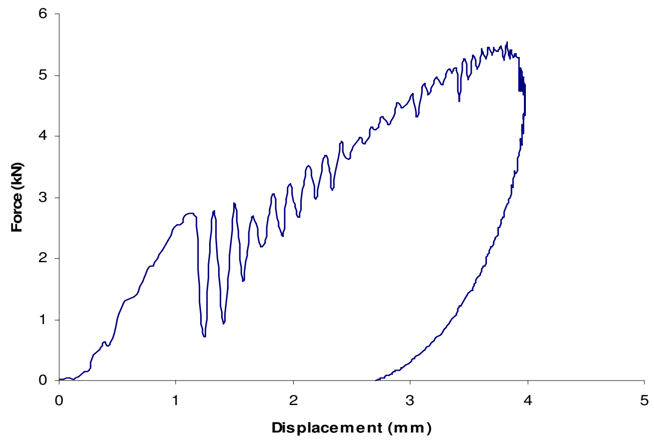

Fig. 8 Representative force – displacement plot for the [0/90]$_{6s}$ laminate.

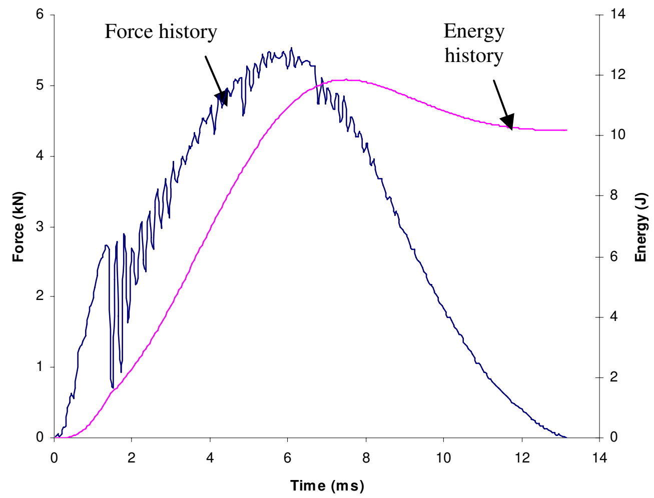

Fig. 9 Representative load and energy against time plot for the [0/90]$_{6s}$ laminate.

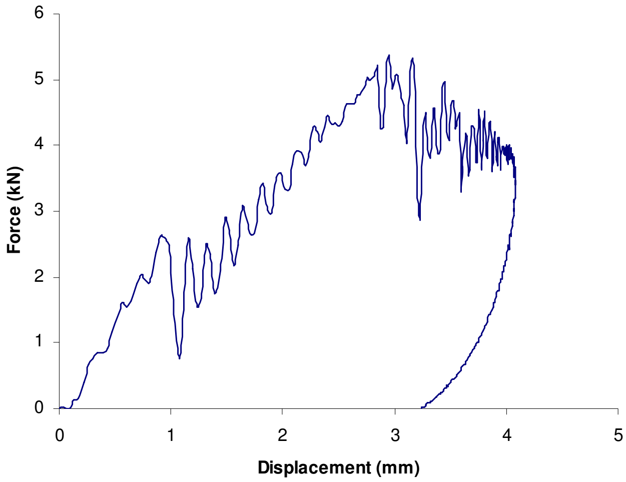

Fig. 10 Representative force – displacement plot for the [0/45/90]$_{4s}$ laminate.

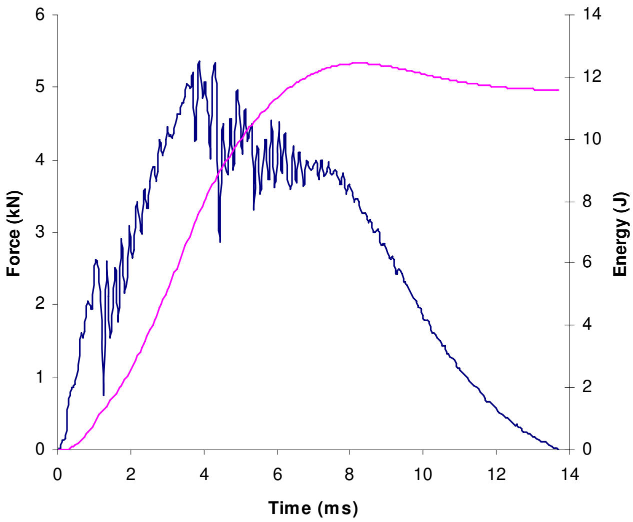

Fig. 11 Representative load and energy against time plot for the [0/45/90]$_{4s}$ laminate.

7 Sectioned photographs of the laminates

Physical examination of the composite laminate after impact revealed the modes of damages such as indentation, surface cracking, delamination and back face splitting. The separation of the back ply followed a pattern of crack that reproduces the fibre directions.

Figs 12 & 13 are x10 magnified photographs of the through the impact point sectioned face of the composites. Damages such as indentation and delamination are noticeable. Clear pictures of the complex failure mechanisms were disclosed with microphotographs taken at x50 magnification [*Figs 14 & 15*], exhibiting delamination, matrix cracking etc. The damage as seen seems to be more severe in the $[0/45/90]_{4s}$ laminate compared to the $[0/90]_{6s}$ structure, noting that geometry and thickness is the same for the composites. Thus, this effect is thought to be because of the shearing effect of the 45^0 laminae.

As composites do not deform plastically, they absorb large amount of energy resulting in fracture areas and reduced strength and stiffness. In a low energy impact, such as this, the damage towards the bottom is mainly because of bending stresses and the mis-matching of bending stiffness.

Fig. 12 Macro-photograph of the sectioned face of the $[0/90]_{6s}$ composite plate.

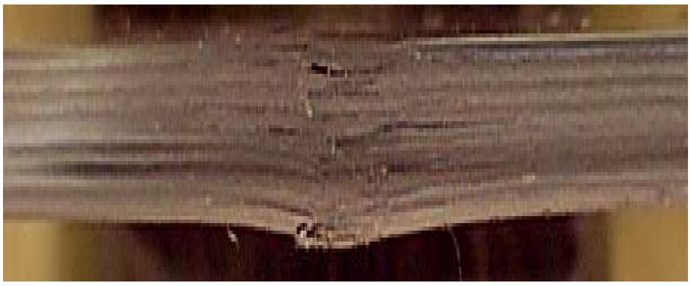

Fig. 13 Macro-photograph of the sectioned face of the $[0/45/90]_{4s}$ composite plate.

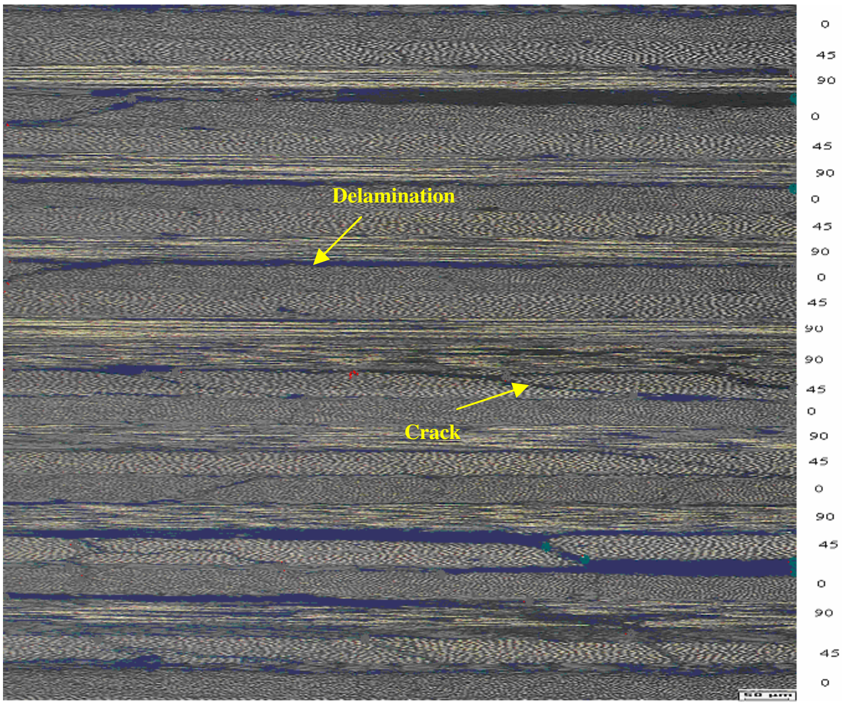

Fig 14a Micro-photographic image of through the impact face section of the first $[0/45/90]_{4s}$ laminate.

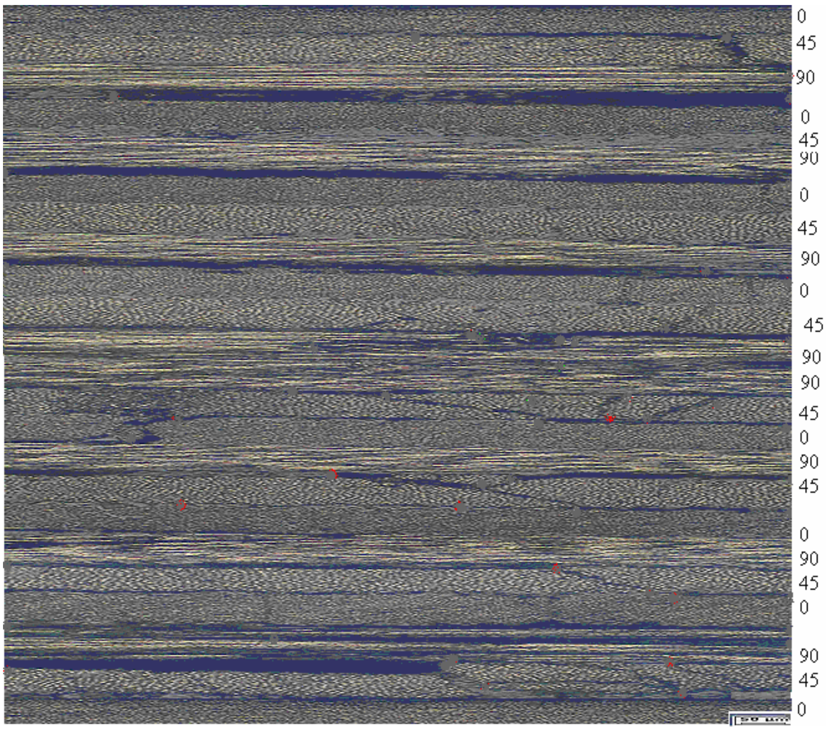

Fig 14b Micro-photographic image of through the impact face section of the second $[0/45/90]_{4s}$ laminate.

Fig 15a Micro-photographic image of through the impact face section of the first [0/90]$_{6s}$ laminate..

Fig 15b Micro-photographic image of through the impact face section of the second [0/90]$_{6s}$ laminate.

8 Absorbed impact energy

When a composite structure is subjected to impact, part of the energy associated with the impact is used for elastic deformation of the material. The energy in excess is dissipated through several mechanisms, such as fibre breakage, delamination, fibre-matrix debonding and matrix cracking.

An important parameter in assessing the energy absorption capacity of a structure is the energy absorbed per unit mass, sometimes referred to as the specific energy absorption [7]. It provides an idea about the energy absorption efficiency of a structure. In this study the composite plates are of the same dimensions and mass, only the stacking sequence is different. The energy absorbed by the plate is an indication of the magnitude of damage.

From *Tables* 4a & 5a the $[0/90]_{6s}$ laminate absorbed 9 J of energy, compared to 11 J for the $[0/45/90]_{4s}$ plate. Hence, the $[0/90]_{6s}$ composite offered better resistance to damage this is likely to be because of the shearing effect on the 0/45/90 interfaces being greater than the 0/90 interface, implying different through the thickness crack paths. The numerous drop and rise (stick-slip) of the angle-ply laminate (*Figs 8 to 11*) after the peak load is an indication of a more complex and greater magnitude of damage.

9 Impact performance of laminates

The impact response such as peak load, damage threshold, energy to peak load, time to peak load, maximum deflection and absorbed energy were obtained from the dynamic display of the composites.
The contact time between the impactor and the laminate is longer for the $[0/45/90]_{4s}$ laminate. The values were 13.2 ms and 13.6 ms for $[0/90]_{6s}$ and $[0/45/90]_{4s}$ composites respectively. Also Hertzian failure respectively occurred at 1.35 ms and 1.2 ms respectively. These failure loads were 2.7 kN and 2.63kN respectively as shown in *Tables* 4b and 5b. After the failure, the contact loads dropped sharply because of stiffness reduction, maybe due to delamination or fibre breakage. Based on the high drops on load it is likely that delamination has occurred [6].

The bending stiffness is an indication of the toughness and the ability of the composite to absorb energy. It depends to some degree on the manner in which the load is applied. Engineering theory shows that the flexural stiffness of any panel is related to the cube of its thickness [8, 9]

Stiffness is an important property of a structure. We may say a stiff material is one with a high value of elastic or bending modulus *E* and a stiff structure is the one with a high value of the second moment of area of the cross-section *I* [10]. In composites, the cross-section can be identical or the same, but stiffness improved by an appropriate configuration of laminae [11].

The slope of the ascending section of the load – displacement plot is the bending stiffness, due to its representation of the stiffness of the plate under impact-induced bending, at the beginning of the impact regime. The bending stiffness of the angle ply composite is 1.69 kN/mm, as against 1.36 kN/mm for the cross ply laminate, implying that the later was less resistant to bending.

Table 4a Impact characteristics of the cross-ply laminate

$[0/90]_{6s}$				
Test No	Contact time (ms)	Absorbed Energy (J)	Peak load (kN)	Bending Stiffness (kN/mm)
1	13.2	9	5.4	1.33
2	13.2	9	5.5	1.39
Average	13.2	9	5.45	1.36

Table 4b Impact characteristics of the cross-ply laminate

$[0/90]_{6s}$			
Test No	Delamination load (kN)	Displacement at delamination (mm)	Time at delamination (ms)
1	2.72	1.1	1.3
2	2.67	1.2	1.4
Average	2.7	1.15	1.35

Table 5a Impact characteristics of the angle-ply laminate

$[0/45/90]_{4s}$				
Test No	Contact time (ms)	Absorbed Energy (J)	Peak load (kN)	Bending Stiffness (kN/mm)
1	13.5	11	5.8	1.73
2	13.7	11	5.5	1.65
Average	13.6	11	5.65	1.69

Table 5b Impact characteristics of the angle-ply laminate

$[0/45/90]_{4s}$			
Test No	Delamination load (kN)	Displacement at delamination (mm)	Time at delamination (ms)
1	2.65	1.1	1.3
2	2.60	1.0	1.1
Average	2.63	1.05	1.2

Table 6 Deflection of the plates after impact

	Test 1	Test 2	Average
$[0/90]_{6s}$	2.77 mm	2.71 mm	2.74 mm
$[0/45/90]_{4s}$	3.20 mm	3.23 mm	3.215 mm

The longer the contact period between the striker and the plate, the greater the damage incurred and the absorbed energy measured. As shown in the tables above the $[0/45/90]_{4s}$ plate incurred more damage. Also as seen in *Table 6*, the post impact displacement of the $[0/45/90]_{4s}$ plate was greater, implying same.

10 Concluding Remarks

Cross ply and angle ply composite laminates were subjected to dynamic drop impact loads from a height of 40 mm (impact energy of 12 J). The impact responses were obtained as the energy history, force history and load-displacement relationship. The plots exhibited the prominent features of the dynamic loading.

From the responses dynamic characteristics such as contact time, bending stiffness, peak load, absorbed energy, delamination load etc were obtained to compare the effects and demonstrate the capabilities of the laminates. Also magnified macro and micro photographs were taken to disclose the crack paths and damage modes, which include delamination, matrix crack etc.

The impact contact time, absorbed energy and the after impact displacement of the laminates, showed that the $[0/45/90]_{4s}$ plate suffered more damage from the same magnitude of impulsive load. It is relevant to notice that due to the stacking sequence and crack path the same composite laminate ie the $[0/45/90]_{4s}$ was more resistant to bending.

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