The Study of Reversible and Irreversible Impact Loading on Symmetrical and Unsymmetrical CFRP Composite Laminates

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Summary

This paper examines the impact response of symmetrical and unsymmetrical laminates. Special attention is given to the stacking sequences used in various applications. Experimentally, load histories of the specimens are obtained; and a scheme for detecting the emergence of delamination noted. Delamination was always accompanied by matrix cracking. Thickness and stacking sequence significantly affected the impact response. The loading and un-loading force – distance plot of the symmetrical plate are closer and similar, indicative of less energy absorption compared to the unsymmetrical plate. But in both cases, near the peak a sudden load drop occurs followed by high frequency oscillations.

Introduction

Carbon / glass reinforced organic / plastic matrix composite materials are increasingly being used as primary structures in the aerospace, marine, automotive, chemical processing and civil infrastructure industries. These materials are such that, through the appropriate arrangement of the stacking sequence, fibre orientation, thickness and material properties of each layer, the strength and stiffness of the laminated fibre-reinforced composite laminate can be tailored to satisfying a specific requirement. But these composites are highly susceptible to impact damage because of their lower transverse tensile strength. The structural behaviour is a function of the in-plane stiffness matrix [A], the flexural stiffness [D] and the extensional / flexural interaction (coupling) stiffness matrix [B], as illustrated in fig 1.

Composite materials are heterogeneous and anisotropic, this makes it difficult to characterise the dynamic behaviour of the structure. They are subjected to a wide spectrum of loading in service and may be required to endure impact loading, blast or shot and static loading. These loads induce regions of high stress concentration in the vicinity of the contact area. It is therefore pertinent to determine the conditions under which the deformation is elastic or inelastic. There are basically three types of damage modes, namely: matrix cracking, fibre

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breaking and delamination. Among this delamination plays a key role in the degradation of the mechanical properties of the material. If a composite is subjected to normal low-velocity (< 10m/s) impact of sufficient energy, it may incur invisible internal delamination at the interface between adjacent cross plies.

A theory describing the local indentation of two bodies in contact was developed by Hertz [8], who analysed the contact of two bodies as an equivalent problem in electrostatics. A solution was obtained in the form of a potential, which described the stresses and deformation near the contact point as a function of the geometrical and elastic properties of the bodies. The result, although both static and elastic in nature, has been widely applied to impact where permanent deformations are produced. The use of Hertz law beyond the limits of its validity has been justified on the basis that it appears to predict accurately most of the impact parameters that can be experimentally verified [20].

Belingardi and Vadori [3] viewed the influence of laminated thickness in low velocity impact behaviour of composites plates. The stacking sequence of the laminates used were $[0/\pm60]_t$ and $[0/90]_t$; where t = 4, 8 and 16. Global energy absorption increases as the number of layers increases. As the impact energy increases, the net value of dissipated energy increases. The saturation energy increases in a more than proportional way as the laminate thickness increases, the $[0/90]_t$ stacking sequence exhibit larger values. Damage degree increases with specific impact energy. Chien-Hua Huang and Ya-Jung Lee [4] subjected specimens of carbon – epoxy prepregs to static contact crushing force. Basically, stiffness degradation was the measure of the failure process. Cross-ply and angle-ply laminates of stacking sequences $[90/0]_{4s}$ and $[45/-45]_{4s}$ respectively were used for the investigation. The force – displacement plot showed that the force drops significantly from the point of ultimate failure. The cross – ply laminate absorbed more energy compared to the angle – ply plate

Sun and Chattopadhyay[18] employed the first order shear deformation theory in conjunction with the Hertzian contact law to study the impact of laminated composite plates. Tan and Sun [20] and Sun and Chen [19] studied the impact on the pre-stress laminates using the finite element method with Newmark time integration algorithm. The merit of the three dimensional numerical model is that it can provide detailed information about the stresses and strains, which cause the damage. Thus, it was possible to capture the formation of the impact-induced damage with a very fine mesh. The contact force history is an important aspect of the response of a structure to impact, and is usually used to validate a numerical scheme. Dazhi Jiang and Dongwei Shu[6] obtained the contact force history using the damage constitutive equation instead of the Hertzian contact law used by Tan and Sun[20]. The peak force and duration of the first pulse gave good agreement. The stress distribution in a laminate was analysed, without the consideration of damage and this distribution gave indication of the possible locations of delaminations. It was concluded that the stress causing the first delamination should be that which is first to reach the threshold for delamination.

Seung Jo Kim et al [17] investigated the effect of curvature on the dynamic response and impact-induced damage in composite laminates. It was concluded that as the curvature decreases the response becomes similar to that of a flat panel and as the curvature increases, the maximum magnitude of the contact force becomes higher. The maximum impact force on the $[0_4/90_4/90_4/0_4]$ panel was higher than that of the $[90_4/0_4/0_4/90_4]$ laminate as curvature increased. This was attributed to the outside layer [0^o orientation] becoming stiffer under the influence of curvature. Observation of damage due to impact on flat laminates showed that delamination has a peanut-like shape and propagates along the fibre direction of the lower layer [17]. This was in agreement with the study conducted by other investigators [17]. Cylindrical panels also have the same tendency. However, it was observed that the delaminated areas of the cylindrical shells grow wider than those of the plates. This was due to the curvature effect that is the maximum impact force becomes higher and the impact duration becomes longer in the case of the cylindrical shells.

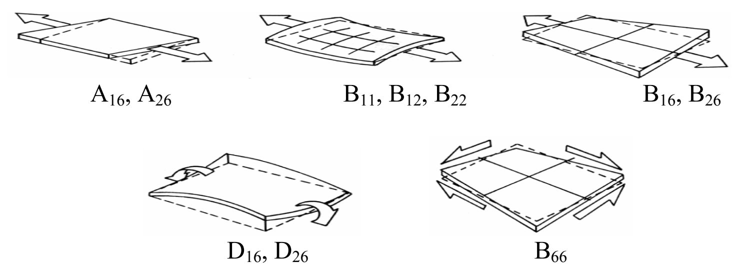

Fig. 1. Illustrating coupling phenomena for laminates [2].

Impactor motion and contact mechanics

Hertz contact law renders a non-linear relation between the applied force and relative approach and the indentation [8], as follows:

$$F = k\alpha^{3/2} \tag{1}$$

Where k is the contact stiffness or coefficient and α is the relative approach. This relationship applies to the loading. The value of the contact coefficient, ***k*** depends basically on the material properties of the target and sphere, and the radius of the sphere. Tan and Sun [20] found this contact to be 4.621 x 10^4 N/mm$^{1.5}$ and 6.641 x 10^4 N/mm$^{1.5}$ for 12.7mm and 19.1mm sizes of indenters respectively. The value of

k for this study was extrapolated to be 6.736 x 10^4 N/$mm^{1.5}$ for the 19.4mm size of indenter that was used.

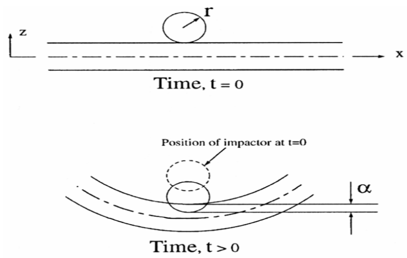

Fig 2. Impact of a spherical mass on a flat plate [12]

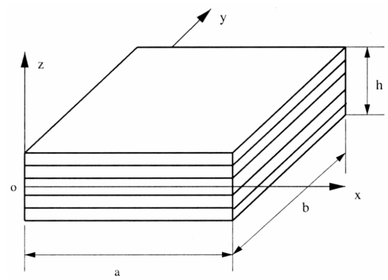

Fig 3. Geometry and coordinate system of composite laminated plate [10].

Material and Sample preparation

The samples for the test were prepared from a roll of prepreg unidirectional carbon-fibre epoxy composite, having 60% fibre volume fraction, using 30^0 and 45^0 squares, and a blade to slice the plies to the required size.

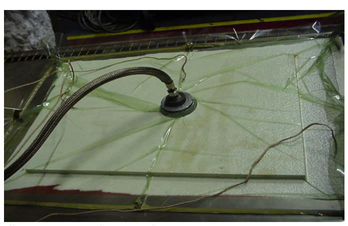

fig 4. Samples under vacuum pressure in the autoclave.

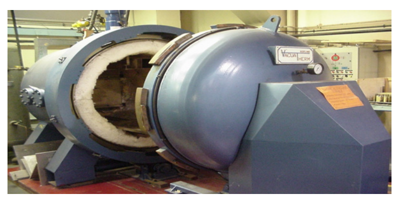

Fig 5. The Autoclave

The stacking of the laminates was made manually. The samples were covered with a release film and placed between Aluminium plates on the bed of the autoclave [fig-5]. This was covered with a bleeding material and a vacuum bag, sealed round its perimeter with a tape. A vacuum pump was connected to the valve fitted to the bagging material. Air was extracted and curing was accomplished in the autoclave as follows:

- A pressure of 700 kN/m^2 was applied.
- Heated to 175^0C at the rate of 10^0C per minute.
- Cured for an hour at 175^0C.

The vacuum generated was maintained through out the curing period. The autoclave was opened slightly, for the specimens to gradually cool to room temperature, before the vacuum pressure was released.

Test Programme

A programme was developed to examine the response of symmetrical and unsymmetrical laminates at low velocity impact (typical 10m/s). Three kinds of laminate configuration were tested and lay-ups as described in table 1.

Table 1

S/N	LAY-UP	NATURE	LAYERS	SUPPORT
1	$0_3/90_3/45_3/30_3$	Unsymmetric	12	Fixed
2	$[45_3/\text{-}45_3/0_3]_s$	Symmetric	18	Fixed
3	$[0_3/90_3/45_3/30_3]_s$	Symmetric	24	Fixed

The sample was rigidly supported in the main unit of the ROSAND impact tester (fig-6) and the falling weight guided onto the sample, in a defined manner and specified velocity. 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. Also stored is the displacement. The fracture event last, typically for a few thousandths of a second. Tests were repeated for two samples of each lay –up configuration and little variation of the peak and delamination loads were observed.

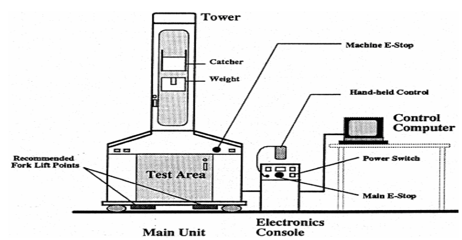

Fig 6. Features of the ROSAND impact tester

Experimental results

Matrix cracks are believed to be the first type of damage introduced during impact. However, matrix crack tips act as initiation points for delamination and fibre breaks that can dramatically change the local and / or global strength of the composite and affect the behaviour. An impact specimen can absorb the impact energy by various laminate level failure mechanism including:

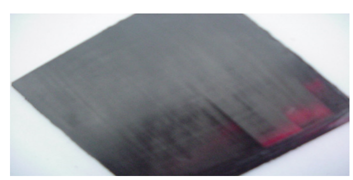
fig 7. Photograph of $[45_3/\text{-}45_3/0_3]_s$ sample after the impact test.

- Impact face indentation, indicative of local matrix crushing.
- Local fibre breakage.
- Interlaminar delamination.
- Back face splitting.

The delamination load is the value of the force that initiates the first ply separating in the laminate. It is sometimes referred to as the **delamination threshold load (DTL).**

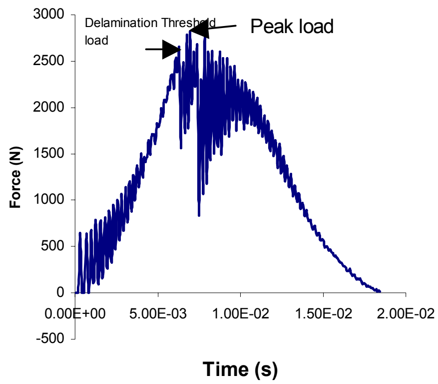

Fig 8. force – time for an 18 ply laminate $[45_3/\text{-}45_3/0_3]_s$ subjected to an impact energy of 5J

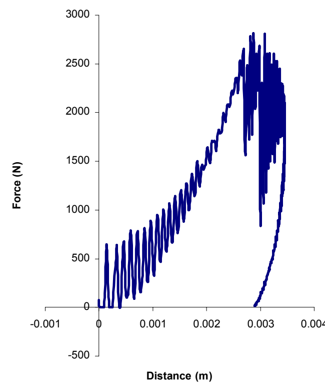

Fig 9. force – distance for an 18 ply laminate $[45_3/\text{-}45_3/0_3]_s$ subjected to an impact energy of 5J

The experimental curves contain some small oscillations during the loading portion and deviate from a pure half sine wave. The minor peaks in the load history plot up to the peak are basically due to elastic wave responses and vibration of the specimen; while the change in direction of the slope is associated with the introduction of intraply transverse matrix cracking or localized indentation of the specimen. The point on the load history where a sudden or drastic reduction in the load occurs gives the delamination threshold load. The table below shows the value of the delamination and peak loads.

Table 2

S/N	Laminate	Delamination. threshold load (N)	Peak load (N)	Impact energy (J)	Remark
1	$[45_3/\text{-}45_3/0_3]_s$	2641.8	2810.15	5	visible failure
2	$[0_3/90_3/45_3/30_3]_s$	Not visible	2538.2	5.89	no visible failure
3	$[0_3/90_3/45_3/30_3]$	1670.55	1955.45	5.89	visible failure

It can be seen that the force – time plot for the symmetric laminate is much closer to a pure half sine curve compared to the unsymmetric. It is thought that this is because of the coupling stiffness matrix [B] being zero i.e. there is no coupling between the force and moment terms to the mid-plane strains and mid-plane curvatures.

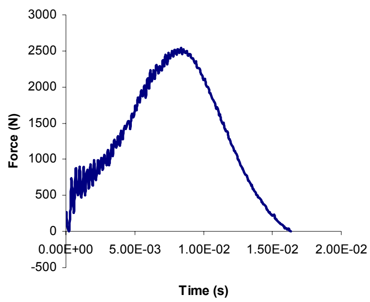

Fig 10. force – time plot for a 24 ply laminate $[0_3/90_3/45_3/30_3]_s$ subjected to an impact energy of 5.89J.

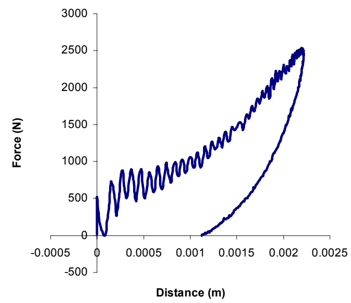

Fig 11. force – distance for a 24 ply laminate $[0_3/90_3/45_3/30_3]_s$ subjected to an impact energy of 5.89J.

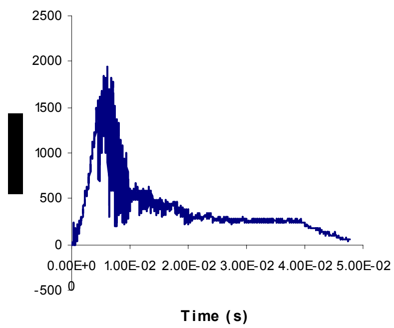

Fig 11. force – time plot for a 12 ply CFRP laminate $[0_3/90_3/45_3/30_3]$ subjected to impact energy of 5.89J.

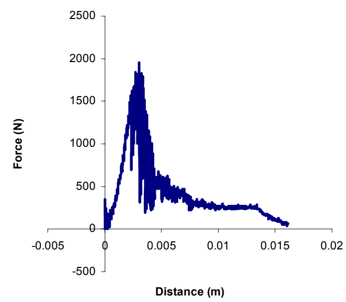

Fig 12. force - distance for a 12 ply CFRP laminate $[0_3/90_3/45_3/30_3]$ subjected to impact energy of 5.89J.

Although the delamination threshold load and peak load have little variation, the damage areas show significant scatter. The delamination threshold load is based on the load at which significant damage initially occurs and does not reflect the final quantity of cumulative damage that occurs. A view of the load – displacement plots for the laminates reveals the following:

- The loading and un-loading curves for the symmetrical laminate are nearly similar and are closer, indicating that little energy is absorbed compared to the unsymmetrical plate.
- The oscillation of the loading decreases as the load increases for the symmetrical plate, till the point of delamination; while it is almost linear for the unsymmetrical plates.

- The un-loading curve gives a nearly non-oscillatory response for the symmetric plate.
- In both cases near the peak a sudden load drop occurs followed by high frequency oscillations.

Conclusion

The contact force history of a spherical projectile impacting on symmetrical and unsymmetrical composite plates were presented here, result revealed that the oscillation of the load decreases, while loading for the symmetrical composite and almost gave a non oscillatory behaviour while unloading. The unsymmetrical plate responded with uniform oscillation as the load increases till the point of delamination. The following details were also observed:

- ❖ Matrix cracking is associated with damage initiation.
- ❖ Delamination is always accompanied by a critical matrix crack.
- ❖ Considerable micro-cracks generates along with delamination growth.
- ❖ There exist a delamination threshold energy above which impact damage commences.
- ❖ Stacking sequence and plate thickness significantly affected the impact resistance of the composite.

The symmetrical force history giving an almost half sine response and the similarity and closeness of the loading and un-loading as seen from the load – displacement plot is an indication of less energy absorption. This may make it preferred and recommended for some structural applications.

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