



A STUDY OF REPEATED IMPACT LOADING ON A SYMMETRICAL CARBON FIBRE LAMINATE

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Abstract

The behaviour of a symmetric laminate under repeated low energy hits of a 12.1mm hemispheric impactor was evaluated. The laminate was able to endure 20 collisions with the striker before perforation. The rate of damage progression was characterised by an equation from the energy profile that correlates the propagation energy and time. The function was represented by a sixth order polynomial. This was differentiated to give the rate of damage evolution. The contact time related to the impact events with the same degree of polynomial. At perforation fibre breakage and matrix cracking were observed.

1 Introduction

Structural materials have been classified as metals, polymers, ceramics and composites. The relative importance of these materials in a historical context was presented by Ashby [1] and quoted in Gibson [5], in which the steadily increasing importance of polymers, composites and ceramics and the decreasing role of metals were clearly illustrated. Also the growing use of composites in structural applications has been reported by agencies such as the Composites Institute of the Society of Plastics Industry, suppliers of advanced composites materials association and the Office of Technology Assessment, U S congress as quoted in [5]. Composites are generally used because they have desirable properties. Although the continuous fibre laminate is used extensively, the potential for delamination or separation of the laminae, is still a major problem because the interlaminar strength is matrix dominated. Damage in composite structures

is often hidden to the eye, but a metal will show a dent or ding.

Composite structural elements are now used in a variety of components for automotive, aerospace, marine and architectural structures. Much of the current composites technology evolved from aerospace applications; between 25% and 75% of the external structures are made of composites. Composites applications in commercial aircraft have been steadily increasing as material cost comes down, as design and manufacturing technology evolves, and as the experience in composites technology continues to increase.

As different forms of impact affect the laminate strength to different degrees, it is difficult to have a single impact parameter to describe the impact resistance. Internal damage such as delamination and back-face splitting can reduce the residual strength of composites significantly [4 & 7]. Delamination, fibre and/or matrix breakage are imperfections, which arise due to an impact energy event. The accumulation of these flaws over time may result in failure of the apparently undamaged structure. These characteristics result in complex interactions between many stress and strain components. Hence the safe use of composites requires an understanding of the progression of damage because of repeated impact.

Validated methods for predicting composite properties and degradation are essential if the engineer is ever to have the confidence to use models of damage development in design. The failure event (however it is defined) in a composite structure is in fact determined by the progressive occurrence and interaction of some or all of the many micro-mechanisms of damage. An important objective is therefore to delay the onset of

catastrophic failure, thus having an engineering component that fails with series of warnings.

Sugun and Rao [13] conducted repeated drop tests over a range of incident energies on glass, carbon and kevlar composites and reported a numerical relationship between the impact energy and the number of drops to failure (perforation). As the incident energy was varied in an arithmetic progression, the number of drops to failure took a harmonic sequence. They also noted that peak load decreases, while total energy increases until failure.

The impact penetration process can be divided into three stages: an initial slope, the fracture zone and the friction stage. The force – time histories contain characteristic features distinguished by the impactor shape used to impact the specimen. Experiments using a round tip, low cone and tall cone impactors were conducted by Kepler [9] who reported that the stiffness of the panels decrease with the pointness of the impactor. A blunt impactor pushes the material inwards and a sharp one pushes the material sideways. In a similar study Kim and Goo [12] showed that as the spherical radius of the impactor increases the maximum contact force becomes higher and impact duration shorter.

Wyrick and Adams [15] subjected carbon/epoxy composites to repeated impact and reported the majority of the damage occurred in the bottom plies and the damage becomes oriented along the fibre direction of the outmost ply on the side opposite the impact. They also noted that an increase in the impact energy reduces the number of hits required to cause perforation and suggested a relationship similar to the working stress diagram.

The choice of the laminate depends on what the designer wants to achieve as components can be tailored to the needs of a project. Composite warpage due to cool down after curing and to hygrothermal environmental variations can be eliminated by the choice of a symmetric lay-up (very relevant for environments of fluctuating temperatures eg space shuttle and marine situations). Composites used in these environments experience periodic impact. The aim of the present study is to provide an understanding of the behaviour of symmetrical composite subjected to repeated impact and to assess the endurance limit.

2 Material

Hexcel[®] manufactured the tape of preregs of unidirectional carbon fibre and epoxy resin used for this study. It contains less than 1% volatiles at 150⁰C or less and a cured resin density of 1.3g/cm³ at 22⁰C as specified by the manufacturers. The material can be used for a period of 12 months or more if stored below –18⁰C.

It has a fibre volume fraction of 60% and a thickness of 0.125mm. The mechanical properties as detailed by the manufacturers are as summarised in *Table 1* below.

Table 1. Material properties

Symbol	Value	Property
E ₁₁	135 GN/m ²	Young's modulus in the fibre direction
E ₂₂	8.5 GN/m ²	Young's modulus in the transverse direction
S ₁₁	1650 MN/m ²	Tensile strength in the fibre direction
C ₁₁	1350 MN/m ²	Compressive strength in the fibre direction
S ₂₂	79 MN/m ²	Tensile strength in the transverse direction
C ₂₂	230 MN/m ²	Compressive strength in the transverse direction
S ₁₃ , S ₂₃	95 MN/m ²	Inter-laminar shear strength
W	198 g/m ²	Nominal prepreg weight
v ₁₂	0.3	Poisson's ratio

3 Manufacturing Process

Using 60⁰ and 45⁰ squares and blades appropriate sizes of laminae were cut from the roll of preregs. Stacking of the plies to form the laminates was made manually. The samples were covered with a release film, and placed between aluminium plates on the bed of the autoclave (see *Fig 1*).

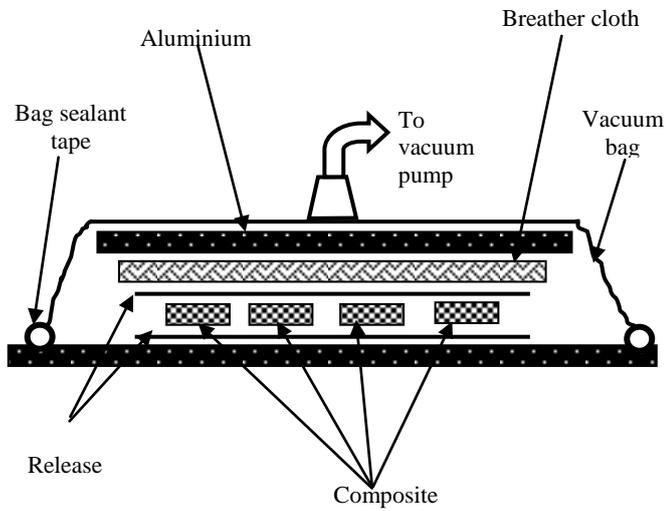


Fig 1. Typical bagging of laminates for curing.

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. The cure cycle is as illustrated in Fig 2.

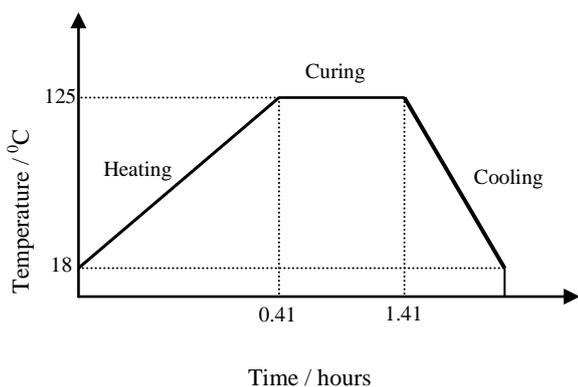


Fig 2. The cure cycle

The vacuum generated was maintained throughout the curing period. The autoclave was opened slightly, for the specimens to gradually cool to ambient temperature, before the vacuum pressure was released. The laminate was made of 24 plies and size 75 x 75 x 3 (mm³). The configuration is $[\pm 45_3/\pm 60_3]_s$.

4 Impact Conditions

Figs 3 & 4 show the clamping fixture of the testing device. It is designed to permit a pneumatic clamp on the specimen at a pressure of 8 bars. The clamp area is circular (1570 mm²) and the area of the coupon being 5625 mm². Table 2 gives a detailed illustration of the impact conditions for this study.

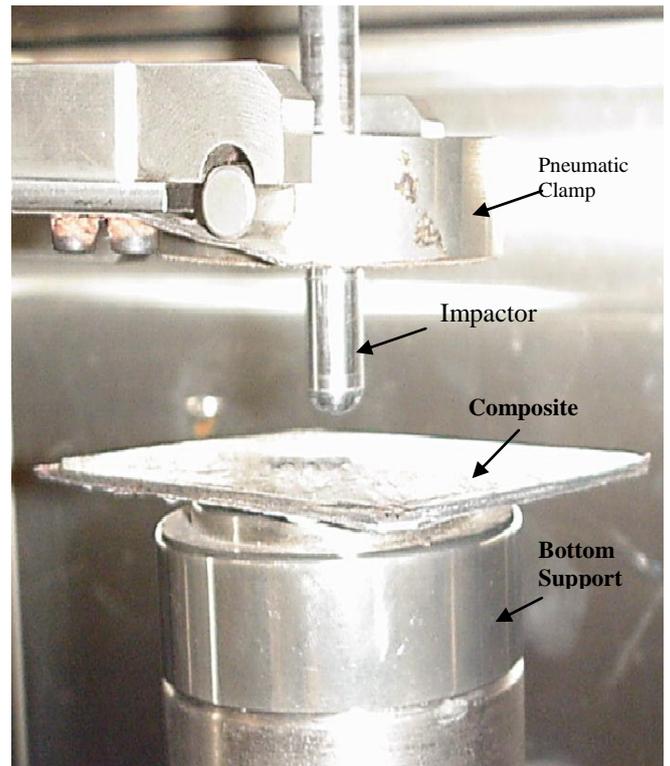


Fig 3. Details of the clamping fixture and impactor geometry

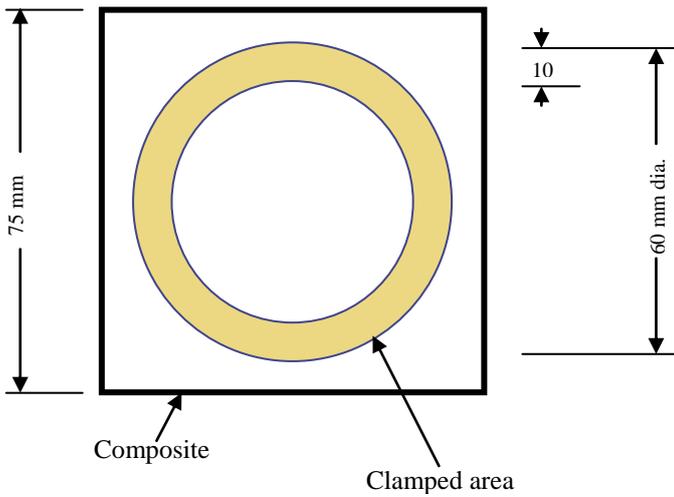


Fig 4. Dimensions of the composite plate and the clamped area.

Table 2. Drop test conditions

No	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	0.02 m
7	Temperature	Ambient (23 ⁰ C)

5 Impact Testing Facility

The basic requirement of the instrumented falling weight test is to gain an understanding of the mechanism by which materials or structures fail in impact situations ie at high rates of strain. Fig 5 is a schematic of the ROSAND instrumented drop weight tester. The consistency of the results from this drop tester as performed on an isotropic material (aluminium) is shown in Figs 6 – 8.

In the main unit the sample is rigidly supported and the falling load is guided onto it. The following also exist:

- Winch to lift the load
- Temperature controlled chamber
- Safety lock

The computer and electronic console:

- Controls the impact process
- Acquires and displays the data
- Stores and retrieves data
- Enables printing of results

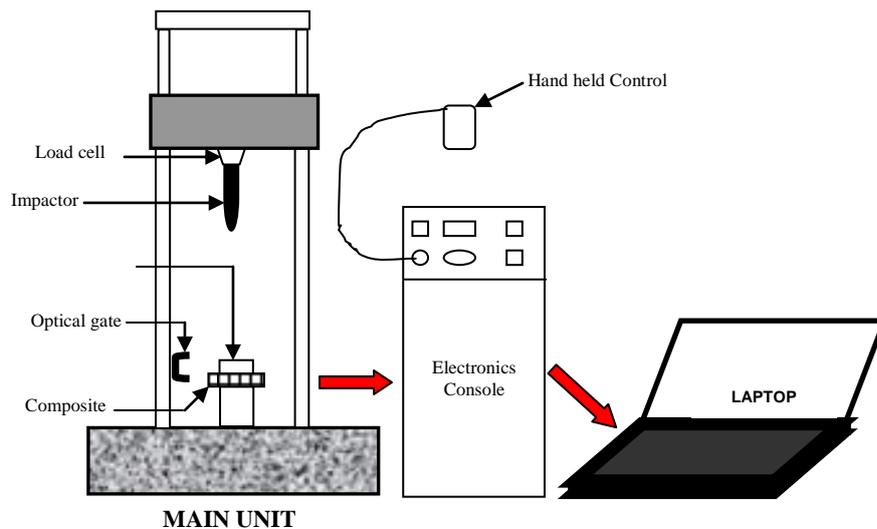


Fig 5. Drop weight impact test set-up

6 Reliability Test on the Instrumented Drop Tester

To ensure the reliability and confidence of the data from the instrumented drop tester, three non-penetrating tests were conducted on 10mm thick aluminium plates. The drop height was 0.03m ie impact energy of approximately 8.8J for the aluminium plates. There are six parameters that define the data capture process: amplifier gain, capture rate (sweep time), number of points, trigger source, trigger level and pre-trigger percentage. The sweep time is very important as it sets the data acquisition speed of the drop tester. In order to preserve as much accuracy as possible for the test, it was set to 50 microseconds per data point.

The results of the tests are plotted in *Figs 6 - 8*. The results as shown below are appreciably consistent; the peak load in each event is slightly above 14,000N and the energy dissipated approximately 5.7J, in all the tests conducted on the aluminium plate.

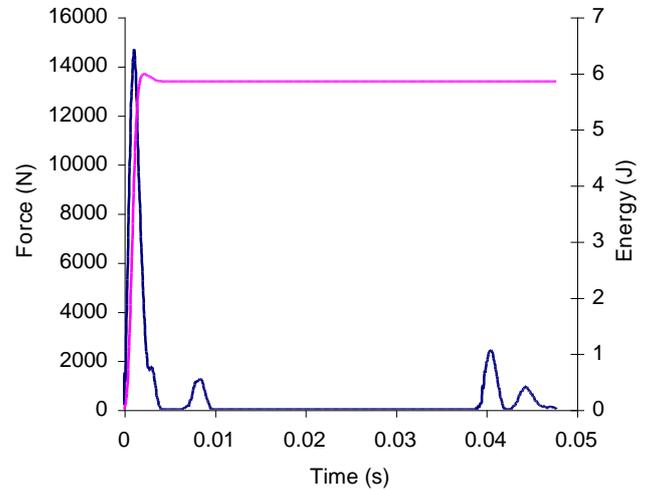


Fig 7 Impact test on second aluminium specimen

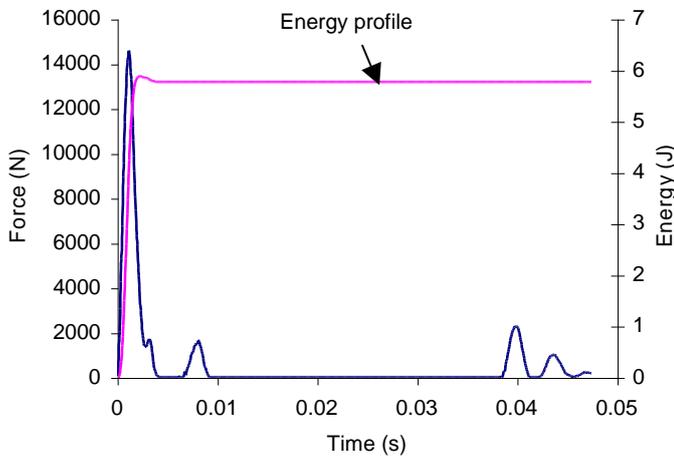


Fig 6 Impact test on first aluminium specimen

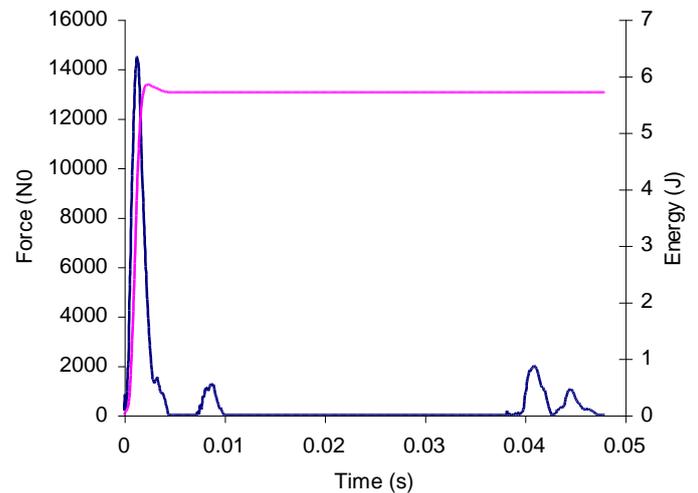


Fig 8 Impact test on third aluminium specimen

7 Transient Data

A sensitive data acquisition system (*Fig 9*) and a load transducer are connected to the impactor. The falling weight is guided through two smooth columns.

The transient response of each laminate was recorded in terms of load, energy and deflection. Load and energy versus time response and load - deflection responses were plotted from representative sample at the energy level. Key impact parameters like peak load, energy at peak load, deflection at peak load and absorbed energy can be evaluated from the data acquired.

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, as it is brittle. Impact energy is initially absorbed through elastic deformation till a threshold energy value (delamination load). Beyond this value, impact energy is absorbed through both elastic deformation and the creation of damage through various failure modes. The type of failure in general depends on material and geometric properties of both impactor and target materials.

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 the 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 represents the history of energy transferred from the impactor to the composite, is calculated.

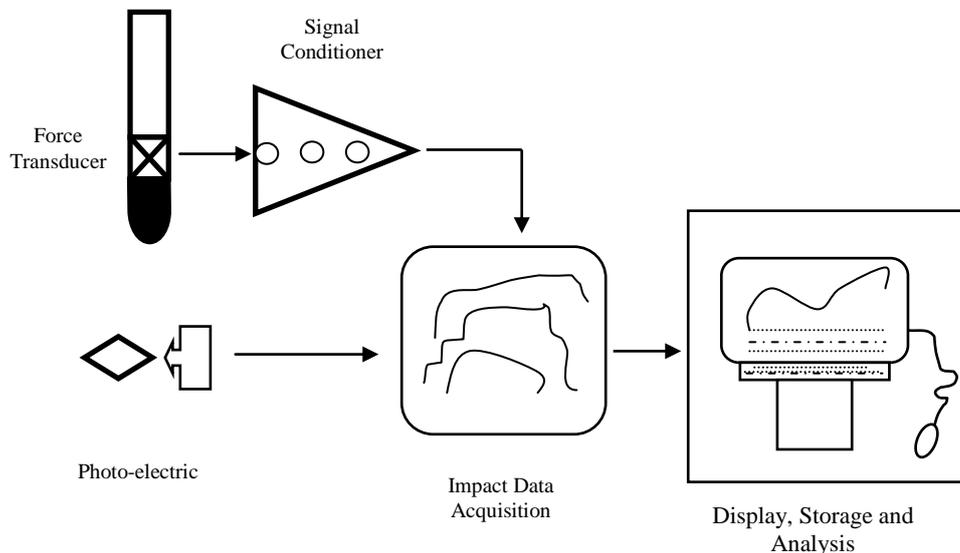


Fig 9. A sketch of the data acquisition system

8 Tested Composite Plates

Macroscopic damage modes of the composite laminate after impact include indentation, surface cracking, delamination, back face splitting and laminate splitting (Fig 10). Among these delamination is an important mode of damage

because the residual mechanical properties of impacted composite laminates are strongly dependent on the delamination areas and their locations at laminate interfaces [7].



Fig 10 Top and bottom sides of the perforated laminates

The macroscopic damage (back-face splitting) follows a pattern of cracks that reproduces the fibre directions, in agreement with the report of Wyrick and Adams [15].

Experimental load and energy histories for the first three consecutive impacts on the sample are shown in Figs 11 - 13. The nominal impact energy for each test was maintained at 5.9 J.

9 Test Results

Although the magnitude of the repeated impact is the same different stress waves propagate through the composite because of the repeated strike by the impactor. The laminate was able to withstand 20 collisions with the impactor before perforation.

In the study the composite is considered failed, when perforation occurs. Perforation is accomplished when the striker completely moves through the laminate. In addition to the laminate configuration, the impact response is affected by the local indentation of the plates. Initially, the plate is flat having an undefined radius, but in subsequent impact there exists an indentation and a finite radius of curvature in the contact zone. This variation is expected as illustrated by the Hertzian law [6 & 14].

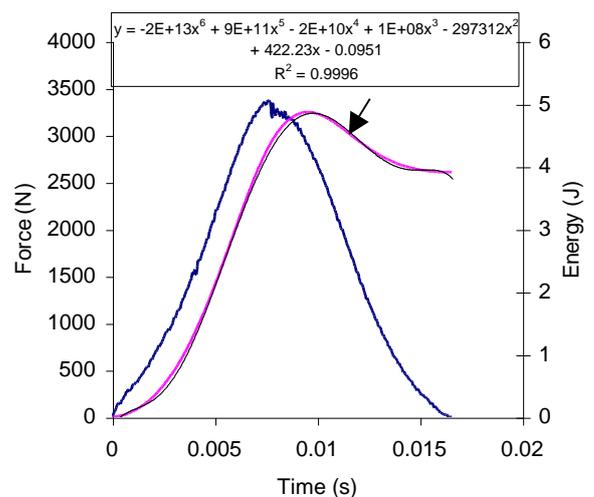


Fig 11. First impact response of $[\pm 45_3/\pm 60_3]_s$ laminate

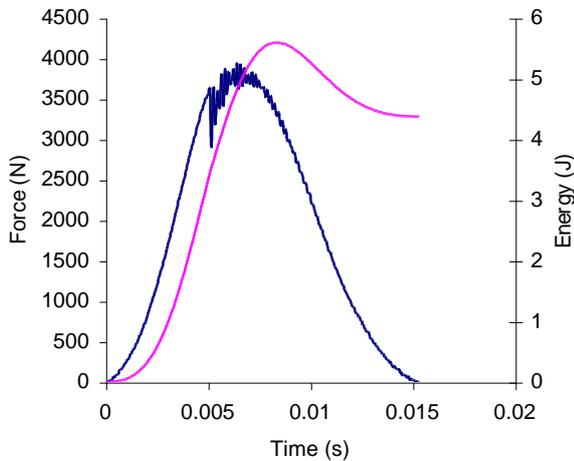


Fig 12. Second impact response of $[\pm 45_3/\pm 60_3]_s$ laminate

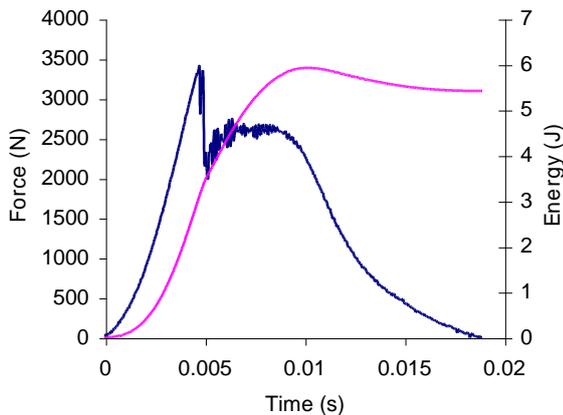


Fig 13. Third impact response of $[\pm 45_3/\pm 60_3]_s$ laminate

The experimental load – time plots contain some salient features and stick-slip type of response and the force history deviates slightly from a pure half sine wave. This is basically due to the interlaminar – intralaminar crack path and localized indentation of the specimen.

The repeated sudden drops in load after the peak, after the first impact test is thought to be because of the scattering phenomena of the crack path, elastic waves or wave interactions. The energy

plot rises to a peak, gradually slopes down and finally forms a plateau, which coincides with the end of the main contact time.

The point on the load history where a sudden or drastic reduction in the load occurs gives the delamination threshold load. This was characterised by Schoeppner and Abrate [11]. They also found the damage threshold load to be more difficult to detect in thin specimens compared to thick specimens ie comparing the magnitude of the impact load with the size of the specimen.

10 Damage Assessments

Perforation was apparent after twenty hits of the impactor, indicative of a slow propagation of damage. This was mainly due to the crack pattern and elastic absorbing mechanism of the symmetric plate.

Damage evolution in the impact process can be connected to the different failure mechanisms (eg matrix cracking, fibre breakage, delamination, etc). The energy utilized for any work done on the composite at any specific time can be obtained from the corresponding point on the energy plot. The line of best fit through the energy data gives a sixth order polynomial relationship, with an R^2 value of approximately 1 (see Fig 11).

$$E = -\lambda_6 t^6 + \lambda_5 t^5 - \lambda_4 t^4 + \lambda_3 t^3 - \lambda_2 t^2 + \lambda_1 t - \lambda \dots [1]$$

$$\frac{dE}{dt} = -6\lambda_6 t^5 + 5\lambda_5 t^4 - 4\lambda_4 t^3 + 3\lambda_3 t^2 - 2\lambda_2 t + \lambda_1 \dots [2]$$

$$\frac{dE}{dt} = -At^5 + Bt^4 - Ct^3 + Dt^2 - Et + \lambda_1 \dots [3]$$

Where A, B, C, D, E and λ_1 are damage constants for the composite plate and dE/dt is the rate of damage evolution for the impact event.

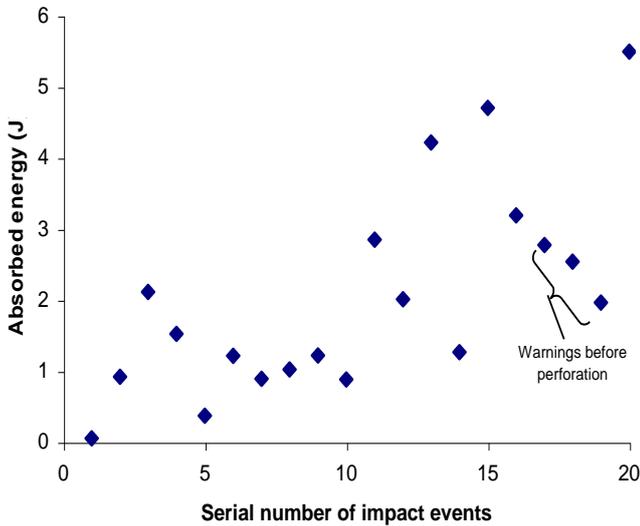


Fig 14. Absorbed energy for symmetric laminate

The energy absorbed at each impact event is as shown in *Fig 14*, for the symmetric laminate. The trend is thought to be dependent on the plate thickness and the crack path of the laminate due to the impact load. The bending of the fibres, which is the load bearing component, is characterised by the fibre on the impacted face being in compression and the other side in tension.

The symmetric plate endured a significant number of impact hits, delaying the onset of penetration with three ‘warnings’ before perforation, ie physical indication of penetration. These warnings were in the form of the fibres on the rear surface showing evidence of fracture. There may have been internal fracture of fibres before this, but these could not be seen.

11 Impact Period

A measurable end of contact (the primary contact) time can be detected; when the force between the specimen and the striker returns to zero. In the case of perforation, there exists a secondary section due to friction between the impactor and the

composite and the contact force remains approximately at zero.

Figs 15 is a plots of the contact time observed during the test. It shows a monotonic rise, and then becomes almost stable and finally some increase because of the complete penetration. It is important to note here that the plot has taken a sixth order polynomial, which was the same as for the energy history.

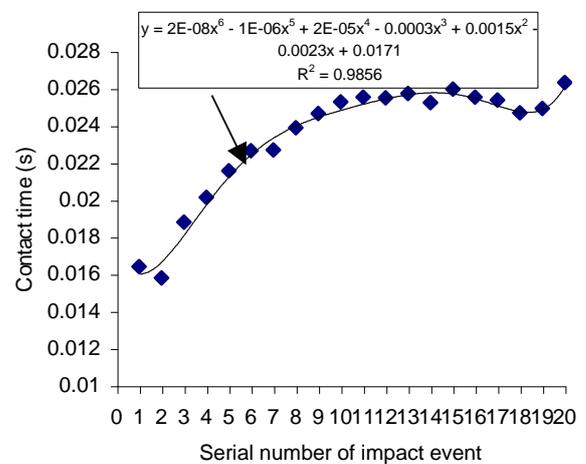


Fig 15. Contact time for symmetric laminate

12 Stiffness of the Laminate

Impact bending stiffness has been known to be an important property in assessing the damage resistance of a composite in particular to delamination [2]. It changes with the configuration of the composite laminates. The force – displacement curves for the strike (*Figs 16*), rises to a maximum and returns to the abscissa.

The slope of the ascending section of the load – displacement plot is the bending stiffness. It represents the stiffness of the plate under impact-induced bending, at the beginning of the impact regime. As shown in *Fig 16*, the bending stiffness of the symmetric plate is 1MN/m.

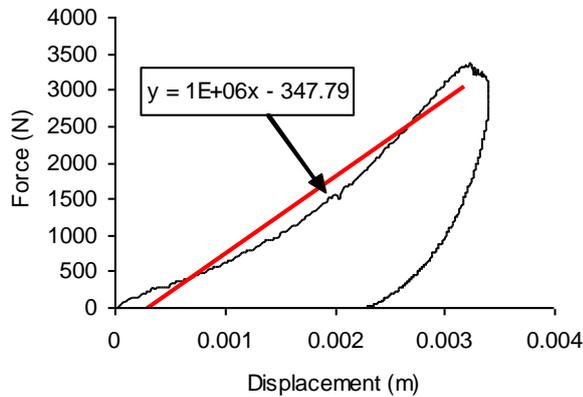


Fig 16 Force – displacement plot for the symmetric laminate.

13 Conclusions

Transient data were obtained as a result of drop tests on a symmetric laminate. It was able to withstand 20 hits of the striker before perforation. The perforated surfaces revealed the fibre orientation of the rear laminae, ie matrix cracking and back face splitting.

The data correlating the absorbed energy and the impact events revealed that the symmetrical plate endured several collisions with the striker before perforation. The progression of damages in the impact event was connected to the formation of the failure mechanisms, by correlating the energy profile to the contact time, giving a sixth order polynomial function, which was differentiated to get the rate of damage formation. The energy profile of an impact event and the plot of the contact time vs the impact events both resulted in a sixth order polynomial relationship.

The limitation of this study is that the impactor stroked the composite repeatedly at the same point, but in reality impact is expected on several parts of a composite structure in service. This is likely to be the subject of the next study.

14 References

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