Abstract

E-glass composites are versatile materials for aerospace and armour applications due to their high specific strength, better energy absorption and low cost. The present study has been attempted for quantitative determination of damage area through thickness in E-glass composite laminates using immersion type ultrasonic C-scan technique. Two different laminates namely E-glass/phenolic and E-glass/epoxy were prepared through hot pressing method with thickness of 10mm and 25mm. The laminates were subjected to ballistic impact against 7.62 x 39 mm projectile with strike velocity of 720±10m/s and their energy absorption is determined. Extent of damage due to ballistic impact is determined quantitatively by measuring the ultrasonic time of flight of the defect echo through the thickness. It is observed that the extent of damage increases from entry point of projectile to exit point along its path of the projectile. It is also observed that E-glass/epoxy shows lesser damage area than E-glass/phenolic laminates for both the thicknesses. Laminates which has undergone more damage area due to ballistic impact has shown higher energy absorption. The method described in the present paper is highly useful for understanding the failure behavior of composites during high velocity impact and the data can be used for designing the improved composites for aerospace and ballistic applications.

Key words: E-glass composites, ballistic impact, energy absorption, ultrasonic C-scan analysis, damage area.

1. Introduction

Fiber reinforced laminated composite materials are widely used in armoured combat systems due to their high specific strength and better energy absorption. Composite armours are usually made up of continuous fibre reinforced either in thermoset or thermoplastic matrix systems. During service, these composite armors are subjected high velocity projectile or splinters impact. Hence it is expected that the composites should have an adequate strength and toughness to withstand and absorb high velocity impact energies. However some defects in composites laminates are expected during fabrication and also usage. The defects like delaminations are formed through impact damage. Delaminations occur due low transverse and interlaminar shear strength of fibre reinforced composite laminates. The depth which the delaminations are produced varies and it is important to determine this depth by using non-destructive test (NDT). An aspect of particular concern for NDT community is the detection and sizing of impact damage in composites through thickness of the laminates.

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Various NDT techniques were reported in literature to characterize the delamination and damage areas in composite laminates. Among the different techniques Ultrasonic C-scan analysis is most promising technique for detection and determine the damage through thickness immersion type testing is time of flight and amplitude based imaging technique. Many researchers have reported on post impact damage of laminate composites using various NDT techniques. Nayak et al. [2] were used immersion type ultrasonic C-scan technique to estimate the internal damage of ballistically impacted thermoplastic and thermoset based aramid composites. They observed that in the similar range of impact velocity the damage area is higher in composites made from thermoplastic resin as compared to thermoset resin. Samant et al. [3] also investigated the core damage area of projectile impacted Kevlar-polypropylene composites using the immersion type ultrasonic C-scan method. They found that core damage area depends on the striking velocity of the projectile. Hosur et al. [5] studied the effect of impact energy (3-30J) on delamination area of carbon/epoxy composites through ultrasonic imaging. They concluded that in addition to impact energy, mass and velocity of impactor, different lay-ups and thickness of composite also affect the delamination area. However all these studies were highlighted on determining the damage area on surface of the laminates. It is very important to determine the damage area of the laminates across the thickness. Therefore the objective of the present paper is to find out the post impact delamination area of the laminates across the thickness. Two important ballistic grade composite laminates viz. E-glass/epoxy and E-glass/phenolic having two different thicknesses of 10mm and 25 mm. These laminates were initially impacted by 7.62 mm mild steel projectile at 720±10 m/sec velocity to induce the damage.

2. Experimental details

2.1 Materials & fabrication of laminates

Diglycidyl ether of bisphenol-A (DGEBA) epoxy resin (LY556) with hardener Diethyle toluene diamine (DETDA) (HY5200) supplied by M/s. Huntsman Chemicals were used in present studies. Commercially available phenolic resin (Resole grade) and E-glass woven roving having 0.25mm thickness and 360 GSM with warp and weft of 55x50 per 10 cm width was used as reinforcement. E-glass/epoxy and E-glass/phenolic composite laminates of sizes 350 mm x 350 mm were made through hand layup technique followed by hot pressing under hydraulic pressure details of the laminate curing is given elsewhere [1]. Thickness of fabricated composite laminates was controlled at 10±0.2mm and 25±0.2mm. Specimens were cut in to the dimensions of 300x300 mm for impact tests.

2.2 Ballistic impact test

Ballistic impact tests were carried out using 7.62 x 39 mm mild steel core service ammunition. The projectile was fired from AK-47 rifle at a distance of 10 m from target at normal impact angle. The strike velocity of the projectile was 720±10 m s\(^{-1}\). Targets in size of 300 x 300 mm were cut using diamond wheel cutting machine. Minimum three specimens were prepared for each thickness and velocity. Striking and residual velocity of the projectile was measured and absorbed energy of laminate was calculated using equation (1) given below.

\[ E_{\text{abs}} = \frac{1}{2}m(v_i^2 - v_r^2) \quad \text{......... (1)} \]

Where,
E_{abs} - Energy absorbed by the laminate (J)
V_{i} - Striking velocity (m s^{-1})
V_{r} - Residual velocity (m s^{-1})
m - Mass of the projectile (g)

2.3 Post impact damage evaluation using Ultrasonic C-Scan analysis

Post impact damage analysis of the laminates was carried out using Ultrasonic C-scan evaluation technique. Fig.1. Shows the immersion type ultrasonic C-scanning setup which is used for automated data acquisition and imaging. The setup consists of a three-axis fixture, an immersion tank, add-on cards, software and transducers. The transducer is connected to an ultrasonic board that acts as the pulser, receiver and digitizer of the ultrasonic waveform. Add-on cards control the mechanical motion and pulser/receiver parameters. The software Acq-scan is used to program the scan cycle acquire/display data, carryout data processing and produce a colour-coded display. The transducers used are of the immersion type and the frequency used was 1MHz. A perspex tank of size 1m × 1m is used for keeping the laminate in water couplant. A square region of 200 mm x 200 mm around the impact point on the laminate was selected for testing which covers the total damage area of the laminates. The pulse parameters used in the present tests are pulse width; 3.1µs, pulse amplitude; 200V, filter; 0.5 - 6MHz, Sampling rate; 100MS/s and record length; 5000 samples. For each scan an optimum gain was used which varied from 10dB to 15dB. Determination of damage area across the thickness is described below.

Transducer emits an ultrasonic wave which is then reflected by the interfaces of the material and by defects. At each reflection an echo is observed, the position in the material being a function of time. Selecting a time window is therefore equivalent to selecting a slice of the medium. Hence it is possible to observe the material section by section by selecting the appropriate time window. Depth wise information can be obtained by recording the position of defect echoes in time on the ultrasonic A-Scan and using this time-of-flight information rather than the back-wall echo amplitude to construct the C-Scan. This method is to record the time-of-flight to the first return echo in the A-Scan as a function of position on the sample. This first return echo will normally represent the back wall in the case of a perfect laminate, or the first delamination if the panel has been damaged.

The scan controller moves the ultrasonic probe over the laminate in a regular fashion, and simultaneously the ultrasonic unit provides an analogue output proportional to the time-of-flight to the first reflection in the A-Scan. This analogue output is digitized by a microcomputer. The digitized scan lines collected in this manner are stored on hard disc and are further processed and produce false-colour image of the component suitably scaled with the different thickness ranges being assigned different colours. The image is effectively a plain view of the component, with depth mapping of any internal features. A two-dimentional ultrasonic C-scan performed section by section in pulse-echo-mode, and at different positions of 10 mm and 25 mm thick E-glass composite laminate relative to the impact point. The
ensuing delamination damage was determined by ultrasonic C-Scans using the pulse-echo immersion method for both the laminates in layer wise distribution. By setting a gate on the backwall echo, information about the attenuation of the initial pulse after it has passed through the thickness of the laminate is collected thereby giving the image of the projected damage of the laminate. Layer wise distribution was obtained by successive time delay from the front wall to the back wall echo covering each interface.

3. Results & Discussion

Energy absorbed during ballistic impact of E-glass/phenolic and E-glass/epoxy composites is calculated. Fig. 2 shows absorbed energy against thickness for both composites. It is observed that at 10 mm thickness, both E-glass/phenolic and E-glass/epoxy composite laminates behaved similarly. However, at higher thickness i.e. 25 mm, E-glass/phenolic absorbed higher energy than E-glass/epoxy laminate.

![Fig. 2: Absorbed energy of both composites as a function of thickness](image)

The Fig.3 shows the visual impression of the laminate and the corresponding A-scan & C-Scan image. Fig. 3 b1&b2 indicate A-scan plots for undamaged and damaged portion of the laminate respectively. From Fig.3b2 it is observed multiple defect echos which indicate multiple delaminations through the thickness. In the present study it has been possible to adopt layerwise scanning by locating the depth using time delay to determine the damage at required depth from the top surface of the laminate to assess the damage area across the thickness. The C-Scan image (Fig.3c) is consist of distinct colour regions indicating varying order of severity of damage. The central white area represents the most severely damaged region and is reported as completely damage area. The blue region represents the least damage/unchecked area and the orange is in between in terms of severity of damage.

![Fig. 3: Ballistically impacted composite(a) it’s typical A-scan(b1&b2) and C-scan image(c)](image)
Fig. 4 shows C-scan images of 10 mm thickness E-glass epoxy and E-glass phenolic laminates at different depth from the top surface of the laminate. From the figure it is clear that damage area is increased progressively with the increase in depth of laminate upto 5mm thickness and became constant at rear layers. The trend is found to be same for E-glass phenolic laminate also. However, the damage area of E-glass phenolic laminate is higher as compare to E-glass epoxy laminate at all depth levels. Damage area of both the laminates against depth is plotted in Fig. 5.

Fig. 4: Layer wise C-scan images of E-glass epoxy & E-glass phenolic laminates of 10 mm thickness at different depth (damage areas are given in the parenthesis)

Fig. 5: Damage areas of 10 mm thickness E-glass epoxy and E-glass phenolic laminates at different depth

Fig. 6 shows C-scan images of 25 mm thickness E-glass epoxy and E-glass phenolic laminates at different depth from the impact surface of the laminate. Damage area is found to be similar for both the laminates at initial layers and later it increased exponentially from ~100 mm$^2$ to 360 mm$^2$ in case of E-glass epoxy laminate and upto 500 mm$^2$ for E-glass phenolic laminate as progressed to the rear layers. In this instance also damage area of E-glass phenolic laminate is determined to be more as that of E-glass epoxy laminate. This can be attributed to the weak inter laminar strenght of the E-glass phenolic laminate which allowed to radial delamination of layers and in turn absorbed more energy during impact. Comparison
of damage areas of both the laminates of 25 mm thickness at different depth levels is given in 

Fig.7

![Layer wise C-scan images of E-glass epoxy & E-glass phenolic laminates of 25mm thickness at different depth levels (damage areas are given in the brackets)](image)

**Fig.6:** Layer wise C-scan images of E-glass epoxy & E-glass phenolic laminates of 25mm thickness at different depth levels (damage areas are given in the brackets)

**Fig.7:** Damage areas of 25 mm thickness E-glass/epoxy and E-glass/phenolic laminates at different depth

**CONCLUSIONS**

The time of flight and amplitude based ultrasonic immersion C-scan technique was used to detect and determine the damage area on post ballistic impacted E-glass composite laminates. Some important inferences that can be drawn from the study are:

1. The present technique is capable to determine the depth wise damage of post impacted laminates which is useful input for the laminate designers.
2. Damage area of E-glass phenolic laminate is found to be higher as compare to E-glass epoxy laminate for both thicknesses.
3. The delaminanation area increases with increase of laminate thickness.
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REFERENCES