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Impact Loading on Nanocomposites in Thermal Environment

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Abstract

This study investigates energy absorption of thermally loaded composites and nanocomposites laminates during impact loading. The laminates are prepared by glass fiber/epoxy with and without nano particles in the matrix system. Nano clay and carbon nano tube are used as filliers in the epoxy matrix. The composites specimens are subjected to impact loading at 0° C, 30° C and 60° C temperature environments. A gas gun impact testing facility is used for propelling the projectile of mass 7.6 g and diameter 9.5 mm with hemi spherical nose. The initial and residual velocities of projectile are predicted to find the energy absorbing capacity of laminates. The energy absorption and delamination area of the specimens are analyzed and discussed for the laminates with and without clay. Also, the ballistic limit is predicted for the specimens of nanocomposites made with glass fibers and epoxy matrix, and the effect of temperature on impact resistance is discussed. Analytical model is developed and the energy absorption characteristics are also studied.

Keywords: impact loading; nanocomposites; thermal environment; gas gun;

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1. Introduction

Fibre reinforced polymer composites are widely used in aerospace and defence applications due to their light weight and tailorable properties to meet specific requirements. These composite materials used in aircrafts, military vehicles and armor applications are common potential susceptible field of high speed impact events. Also the composite materials on these structural applications are also exposed to impact loads at various thermal environments depending upon their applications. It is essential to, investigate and understand the performance characteristics of these materials at various temperature environments for enriching the impact resistance during impact events. The

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impact forces induce matrix crack, fiber breakage and delamination which will in turn affect the dynamic behaviour of the material at thermal environment also need to be addressed.

The rapid advancement of these fibre-polymer composites outstripped the understanding of appropriate failure analysis techniques. Sethiet al. [1][2014] have investigated the interlaminar shear strength of glass/epoxy composites at different speed and environmental conditions. They have observed that the interlaminar shear strength of unidirectional GFRP composites decreased under the exposure of above room temperature. In another study [2] on the externally-bonded FRP system under elevated temperatures, the authors found that severe reductions in residual tensile strength and stiffness are observed only at temperatures exceeding the thermal decomposition temperature of the epoxy polymer matrix. GFRP is tested at the exposure temperatures greater than the glass transition temperature of the epoxy polymer. In applications of externally-bonded FRP repair systems that are not bond critical, exposure temperatures of up to 300ºC are permissible for satisfactory residual performance of the FRP system. The flexural properties and failure mechanisms of graphite-fabric epoxy composites subjected to flexural loading are affected by thermal and hygro thermal ageing. Prolonged dry thermal ageing at 170°C causes a shift in the transition point for failure to higher length to thickness ratios of specimens as well as a reduction in the flexural properties. In the extreme case the transition point disappears and failure occurs only by delamination. Hot-wet ageing in water at 50°C or 95% RH results in a drop in the glass transition temperature [3]. Structural carbon/polymer composites were thermally cycled between low temperature in liquid nitrogen temperature and an elevated temperature of 177 °C. The extent of ply-level micro-cracks was measured as a function of cycles up to 1000 cycles as one indicator of suitability for cryogenic containment applications. The choice of material systems, lay-ups, and thermal cycles allowed the study of the effects of the thermal cycle profile, mode I toughness, and cure temperature on the damage accumulation. The addition of a hold period at elevated temperature led to micro-crack initiation after fewer cycles and increased the micro-crack density in all plies for all of the material systems [4]. Abrate (2001) [5] described an energy-balance model in which the incident energy of the projectile was equated to the energy stored in bending, shear and contact effects. The model yielded the maximum force generated during the impact event taking into account both material and geometrical parameters. Influence of nanotechnology and consequent addition of nano particles in composite materials builds new class of nanocomposite with desirable properties for specific application. Enormous studies are reported that enhancement of mechanical properties are estimated in new class of nanocomposites and also many researchers are evidenced that impact resistance, structural integrity and residual properties are increased on this new variety of composites.

Manipulation of desire property is based on particle size, surface modification, surface area and loading. Various polymerization of organic/inorganic nanocomposites, procedures are reported by several researcher. Adding small percentage of nano scale particles such as nano clay and carbon nano tube (CNT) enhances the mechanical properties over traditional composites and damping capacity of the composite laminates during impact loading. These nano scale fillers act as secondary reinforcement for better energy transfer. This is observed in our previous study [6] on modal analysis on pre and post impact of composite laminates. Our other studies, [7 and 8], focused on experiments and analytical model on energy absorption of nanocomposites laminates subjected to impact loading below and above ballistic limits at room temperature. It is observed that the presence of clay enhances the energy absorbing capacity of the laminates during perforation. There are limited studies on impact energy absorption of nanocomposites at thermally loaded environment. Velmurugan et al.[10], studied comparison between modified and unmodified clay as filler elements in the epoxy that revealed homogenously dispersed orgono clay and unmodified clay improved hardness, mechanical properties, thermal properties and stiffness. Moreover, Considerable improvements in properties are estimated in modified orgono clay dispersed epoxy system compares with unmodified clay.

Since the first instigating innovation of coaxial tubes, rolled up by graphite sheet- carbon nano tubes (CNT) from 1991, experimentally and theoretically demonstrated studies reported that CNTs have extraordinary mechanical, thermal and electronic properties over other conventional materials. Due to exceptional properties combined with low density, many research programs have been undertaken for revealing the potential abilities of CNTs. Many researchers also revealed that using CNTs as reinforcement and fillers in polymer matrix improved mechanical properties of composites and it has been interesting area of research for past decade [11-17].

In this study, an attempt is made to investigate and analyze the impact performances such as ballistic limits and energy absorption capacities of composite laminates with and without fillers on various temperature environments through analytical and experimental simulations. Nanocomposites specimens are subjected to impact loading at 0° C, 30° C and 60° C temperatures. Consequent effects and influences of temperature on impact resistance are also discussed.

Nomenclature

$E_{def,}$	Energy absorbed due to deformation
E_{delam}	Energy absorbed due to delamination
E_{frac}	Energy absorbed due to tensile failure of fibre
E_L	Energy lost during impact
$E_{matcrack}$	Energy absorbed due to matrix crack
E_{cone}	Energy absorbed due to moving cone
E_{total}	Total energy absorbed by the laminate
KE_o	Initial energy of the projectile
m	Mass of projectile
M_c	Mass of moving cone
V	Velocity of the projectile
V_o	Ballistic limit

2. Experiments

2.1. Preparation of laminate

Composite laminates were prepared by vacuum bag molding. The WRM glass fibers of 610 gsm were used as reinforcement for preparing the laminates and epoxy was used as matrix system. Two types of fillers Garamite 1958, nano clay supplied by Southern Clay, USA and CNT were used as fillers in the epoxy. The fillers percentage were varied from 1 % to 5% weight of matrix. The layers of glass fiber are placed in a plane surface in which the resin mixture is embedded. The laminate thickness was obtained by placing number of WRM layers. The WRM with 0º/90º orientation having three layers were layered in the laminates. The thickness of the laminate was 2 mm which was obtained from three layers. The cured laminates were cut into 150 mm x 150 mm size and holes were made for mounting the laminates in the fixture.

2.2. Impact testing

The gas gun setup used for experimental investigation is shown in Figure 1(a). A range of impact velocities are obtained by varying the pressure of air in the chamber of gas gun. An air compressor is used for building up the pressure up to 15 bar in the chamber. The projectile is placed in the chamber rear end of the barrel and the air pressure in the chamber is monitored by a pressure gauge. The projectile used for this study is having a mass of7.6 g and diameter 9.5 mm with spherical nose. The initial velocities (project velocity before hit the target) and residual velocities (after penetration) were measured by high speed camera. Laser diode system and fixture for laminates are shown in Figure 1(b).

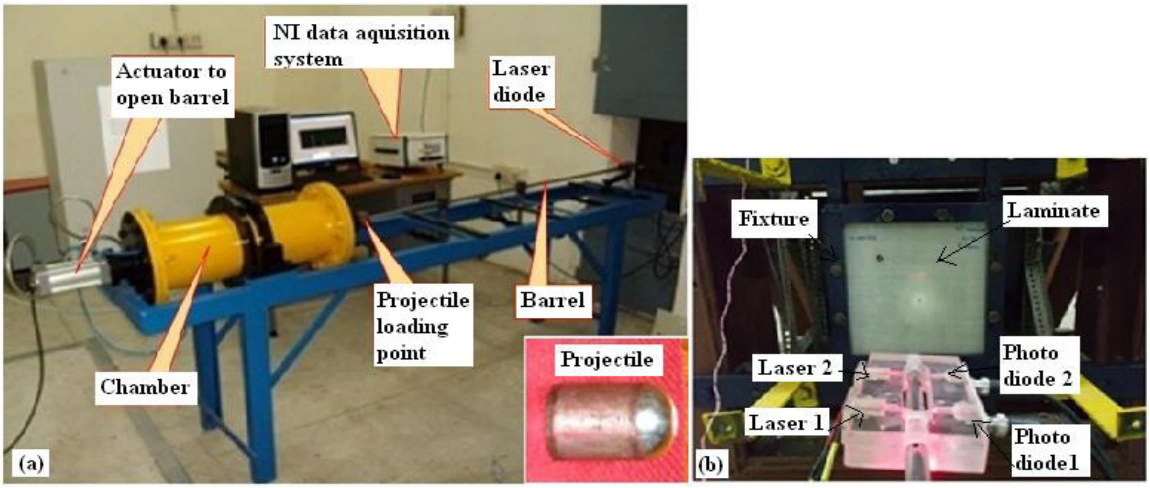

Figure 1: (a) Gas gun setup used for Impact loading, (b) Fixture and laser diode for velocity measurement, Velmurugan and Balaganesan (2014)

3. Analytical model for energy absorption in laminates

During impact and perforation of laminate, the primary fibers in the composite, i.e. fibres directly impacted by the projectile, are strained to tensile failure. The secondary fibers in the composite, i.e. fibres' that are not directly impacted by the projectile undergo deformation. The deformation of the laminate is elastic and the composite reverts back substantially to its original shape after the impact, a small damage area where the fibers are failed. A portion of initial kinetic energy of the projectile is absorbed due to delamination and matrix crack, which is observed on the tested specimens.

Abrate [5] described an energy balance model in which the incident energy of the projectile was equated to the energy stored in bending, shear and contact effects. Naik et al. [9] formulated an analytical model based on wave theory to investigate the ballistic impact behaviour of two dimensional woven fabric composites when subjected to impact loading. Different damage and energy absorbing mechanisms was identified during ballistic impact. In the model, the following assumptions are made.

- The projectile is rigid and remains un-deformed during the impact.
- Projectile strikes the target normally and motion is uniform during penetration in each time interval.
- Energy absorbed due to failure of primary fibers and deformations of secondary fibers are considered independently.

Thus the total energy absorbed is given by,

$$E_{tot} = E_{tensile} + E_{deflection} + E_{cone} + E_{delam} + E_{matcrack} \tag{1}$$

Ballistic limit is given by,

$$V_o = \sqrt{\frac{2}{m} E_{tot}} \tag{2}$$

In the beginning of the first interval of time, the entire energy is in the form of kinetic energy of the projectile. Later this energy is shared by different damage mechanisms, the kinetic energy of moving cone and projectile. Considering the energy balance at the end of ith time interval,

$$KE_o = E_{Pi} + E_{mci} + E_{tensile(i-1)} + E_{deflection(i-1)} + E_{delam(i-1)} + E_{matcrack(i-1)} \tag{3}$$

where, KE_O is the initial kinetic energy of projectile, E_{Pi} and E_{mci} are projectile and moving cone energies at ith instant of time. Rearranging the terms,

$$\frac{1}{2} m V_o^2 - E_{(i-1)} = \frac{1}{2}\left(m + M_{C_i}\right) V_i^2 \tag{4}$$

where, *m* and V_o are the mass and initial velocity of the projectile, M_{C_i} is mass of moving cone at ith time interval

$$E_{(i-1)} = E_{tensile(i-1)} + E_{deflection(i-1)} + E_{delam(i-1)} + E_{matcrack(i-1)} \tag{5}$$

The energies shared in each time interval is explained in [9]. The above energy is for (i-1)th time interval. From eqn.(4) the velocity of projectile at the end of ith time interval is obtained by the following equation,

$$V_i = \sqrt{\frac{\frac{1}{2} m V_o^2 - E_{(i-1)}}{\frac{1}{2}\left(m + M_{C_i}\right)}} \tag{6}$$

The above iteration is repeated till the target fails due to projectile impact and complete perforation takes place.

4. Results and discussions

4.1. Energy absorption at room temperature

Energy absorbed by the laminate is various failure mode is calculated based on Eqn. 5 of time dependant mathematical model and based on our previous study [8] for various failure mode energies. Energy absorption by the laminates subjected to impact velocity of 130 m/s is discussed, for the three layer laminates, with and without clay. The model predicts projectile energy and energy absorbed by the laminate in various failure modes during perforation. Fig. 2 corresponds to laminate without clay subjected to impact with a projectile energy of 64.2 J. The residual energy of projectile after perforation is 10.5 J which is about 16% of initial energy of projectile. The energy absorbed by deformation is about 48%. Energy absorbed in delamination, matrix crack and tensile failure are 11.3%, 5% and 2.2% respectively. The duration of perforation based on model is 20 µs. Figures shows decrease in projectile energy for 20 µs and energy transfer from projectile to laminate in various failure mechanisms. It is understood that the majority of projectile energy is absorbed by the elastic deformation of secondary fibres. The failure of laminates is seen in the annexure.

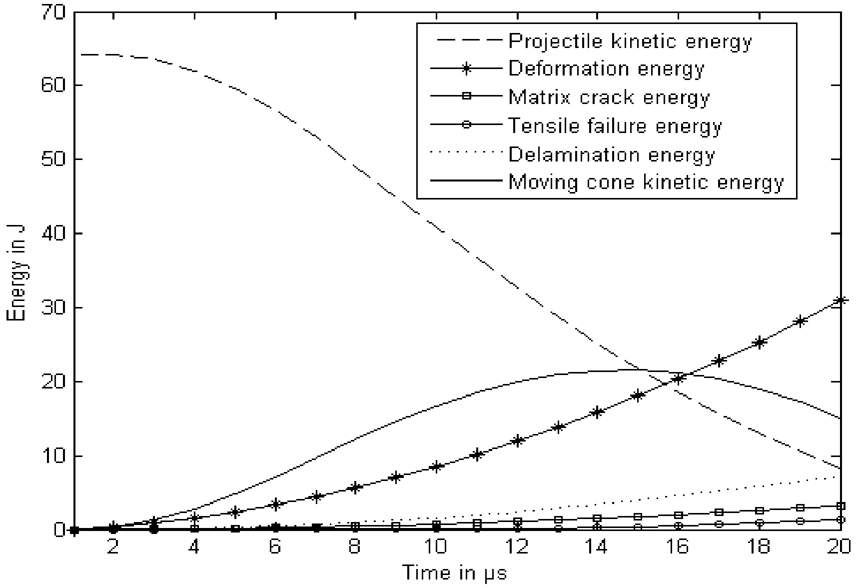

Figure 2: Energy absorbed by three layer laminate without clay at 130 m/s.

Fig. 3 shows the influence of different percentage of clay loading on composite plates. It is been observed that nano clay addition and modification of matrix system dynamically improves mechanical properties, impact resistance and energy absorption in various failure modes. It is observed from Fig. 3 that the nanocomposites laminate having 3% clay absorbs energies of 32.2%, 27.3%, 23.5% and 20% higher than laminate without clay in deformation, delamination, matrix crack and tensile failure of fibers respectively. The laminate having 5% clay absorbs 33.5%, 42.5%, 24.4% and 25.3% of energies higher than the laminate without nano clay in deformation, delamination, matrix crack and tensile failure respectively. The laminate with 5% clay absorbs 31.5% higher energy in delamination when compared to laminate without clay. The model predicts values of various failure mode energies during perforation of the laminates which cannot be predicted from experiments. The experiments for impact loading give the energy absorbed by the laminate from initial and residual energies of the projectile and the failure energies due to delamination and matrix crack can be calculated from the damage area.

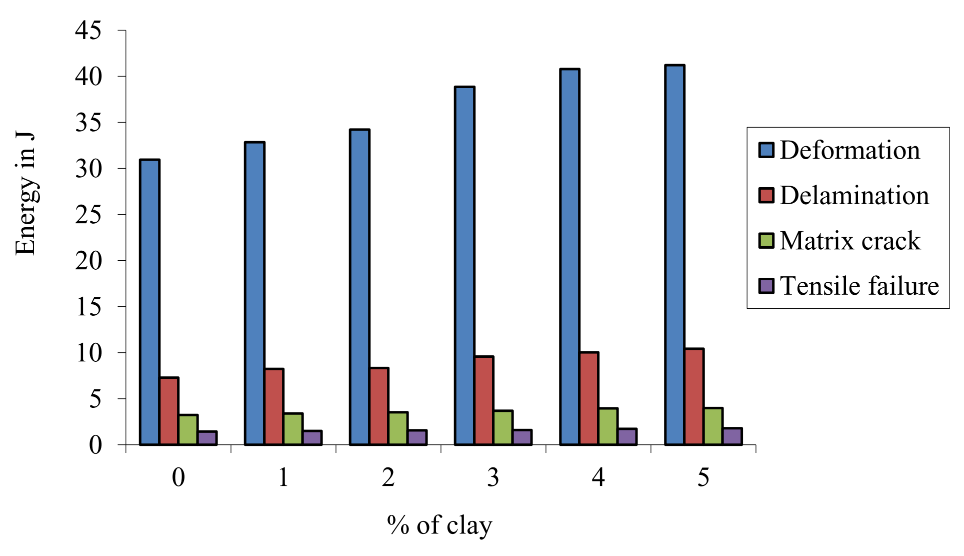

Figure 3: Different modes of energy for three layer laminate with and without clay when subjected to impact velocity 130 m/s

4.2 *Temperature effect on energy absorption and delamination*

The deflection of the laminate occurs due to entry of the projectile that makes slip between the layers, resulting in-plane compression and tension in the rear face of the laminates. These results in separation of layers leads to Mode II type inter laminar crack. The impact produces plastic deformation in the impacted area which is extended by the penetration of the projectile. Matrix crack leads to decrease in inter laminar strength of the composite, as a result, further loading and deformation causes delamination.

The energy absorption of 2 mm thickness glass/epoxy laminates with and without clay subjected to 140 m/s impact velocity at 0°, 30° and 60° C is shown in Fig. 4. The laminates without clay absorb less energy than the laminates with 1-5% clay. The increase in percentage of energy absorption is high for the laminates with 4% and 5% clay when compared to laminate without clay at 30° C. For 0° C target temperature, the increase in percentage of energy absorption for laminate with 2% clay is 25%, when compared to the laminate without clay. Clay dispersion up to 2% shows good improvement in energy absorption. When the laminates are subjected to impact at 60° C, It is observed that the increase in percentage of energy absorption for the laminate with 2% clay and decrease in percentage of energy absorption for the laminates with 3%, 4% and 5% nano clay.When the laminate at 60° C is subjected to impact, the increase in percentage of energy absorption is observed for the laminate with 2% clay when compared to laminate without clay and decrease in energy absorption is observed for the laminates with 3%, 4% and 5%. It is also observed that the laminates with 2% clay and without clay at 0° C absorb more energy than the laminates at 30° C and 60° C.

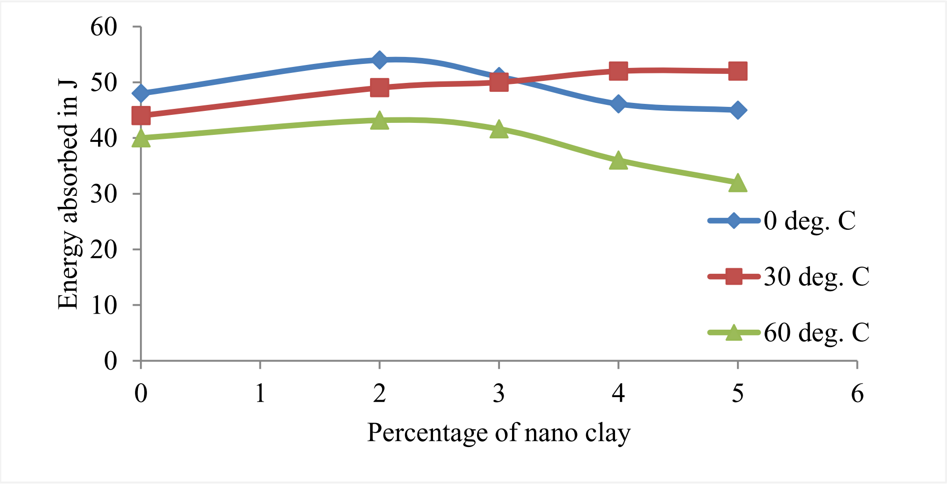

Figure 4: Energy absorbed by nano clay dispered composites laminates at various temperature when subjected to impact at 140 m/s

Fig. 5 shows the variations of delamination area for 2 mm thickness laminates with and without clay on the identical impact events at 140 m/s. At 30°C temperature environment, it is observed that the delamination area of composites with 3% clay is 10 times higher than laminates without clay where the delamination area of the laminate without clay is found to be 6.5cm^{2}and the delamination area for the laminate with 3% clay is found to be 60cm^2. Impact events at 0ºC develop greater area of delamination on the laminates when compared to impact events at 30ºC and 60ºC. The increase in delamination in nanocomposites is one of the reason for increase in energy absorption when compared to laminates without clay.

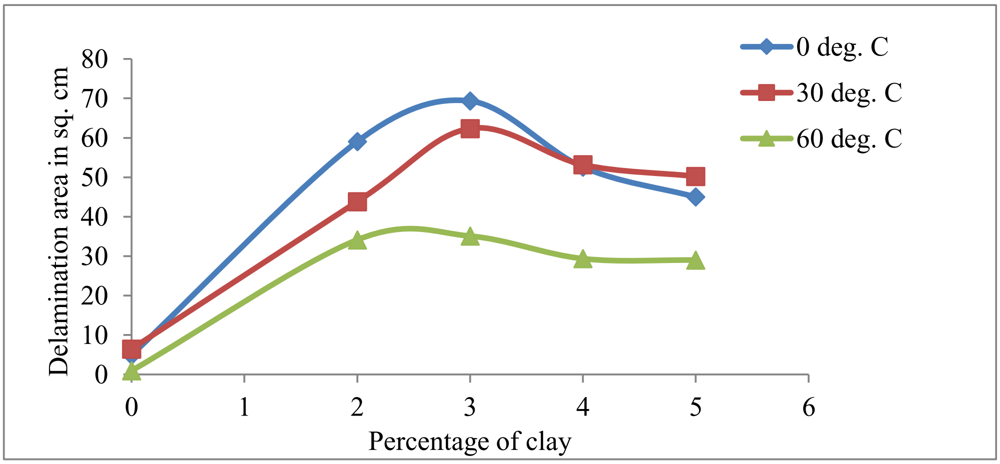

Figure 5: Delamination of the nanocomposites laminates at various temperature for the impact velocity of 140 m/s

Figure 6. Shows the energy absorption characteristic of CNT reinforced glass/epoxy nano composites. Energy

absorption capacities are computed on laminates at 120 m/s at various temperatures ranges (0ºC, 30 ºC and 60). It is observed that 2% of CNT reinforced nanocomposites absorbs more energy than others at all temperatures and overall representation of figure showed that impact loading on CNT nanocomposites at 60ºC absorbs more energy. Increase in rate of energy absorption capacity with respect to temperature is higher on 3% CNT nanocomposites and lower in 0% CNT nanocomposites. Hence trending of graph establishes that increase in nano particles tends to increase overall energy absorption capacity of nano particles dispersed composites. This is due to CNT dispersion which acts as secondary reinforcement in the matrix system. The energy transfer between matrix and CNT is in the form of bending, twisting and compression within the matrix system.

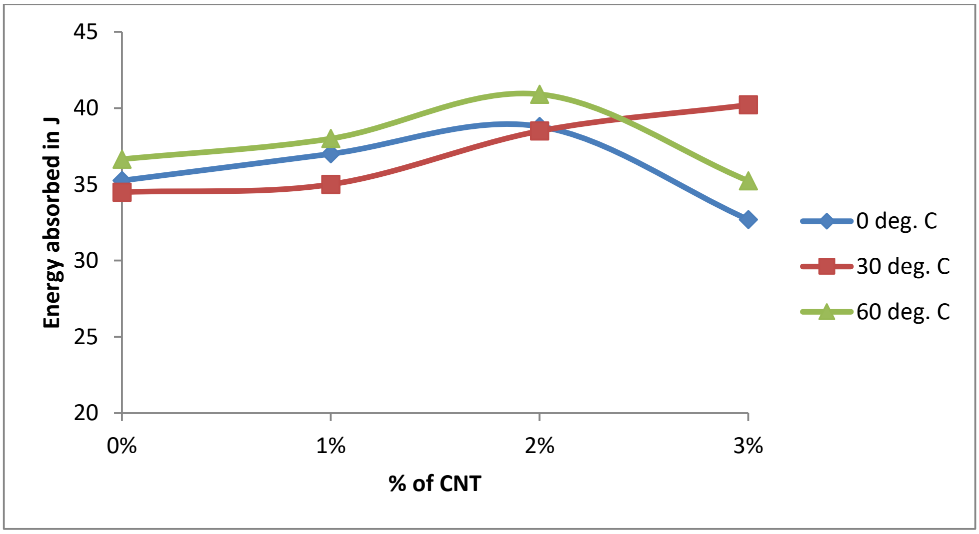

Figure 6. Energy absorbed by the CNT reinforced nanocomposites laminates at various temperature

Fig. 7 in annexure shows the images for delamination area of three layer laminates with and without clay during perforation at impact velocity 140 m/s for target temperature at 0°, 30° and 60° C. The laminates without clay and with clay up to 5% are perforated at this velocity. Figs. 7(a) –(c) correspond to the laminates without clay at 0°, 30° and 60° C . Decrease in delamination area is observed for 60° C. This is due to increase in deformation energy at higher temperature. Figs. 7(d) - 7(f) correspond to delamination area of the laminate with 2% clay at 0°, 30° and 60° C. It is seen that as the clay percentage increases, increase in delamination area is observed for the laminates when compared to the laminate without clay. The failure of fibres is seen in the centre of the delaminated area. This is observed for the laminates with and without clay. Figs. 7(g) - 7(i) correspond to delamination area of the laminate with 4% clay at 0°, 30° and 60° C. There is no much difference in delamination area between laminates with 2% and 4% clay.

5. Conclusion

The nanocomposites specimens are subjected to impact loading at 0° C, 30° C and 60° C temperatures. The energy absorption characteristics and delamination area are analyzed and discussed for various percentage clay and CNT loaded on the matrix. The ballistic limit is predicted for the specimens of nano composites made with glass/epoxy fibers and matrix, and the effect of temperature on impact resistance is also discussed. Analytical model is developed and the energy absorption in various failure modes is also studied for room temperature. The following conclusions are made.

- The presence of clay and CNT in the epoxy matrix system increases the energy absorption capacity of laminates during projectile impact. The laminate with clay and CNT offers better resistance to perforation than the laminate without clay and CNT.
- The laminates with 3% clay and with 2% CNT show optimum improvement for energy absorption in

perforation in impact loading at 0° C, 30° C and 60° C target temperatures.

- Dispersion of clay in the matrix increases the delamination area of laminates during impact loading and hence increases the energy absorbed in delamination.
- The presence of clay in matrix increases the ballistic performance of the nanocomposites. The increase in energy absorption and ballistic limit is observed in laminates with clay up to 5%.
- Nano scale fillers dispersed in the matrix acts as secondary fibers in the composites for energy absorption.

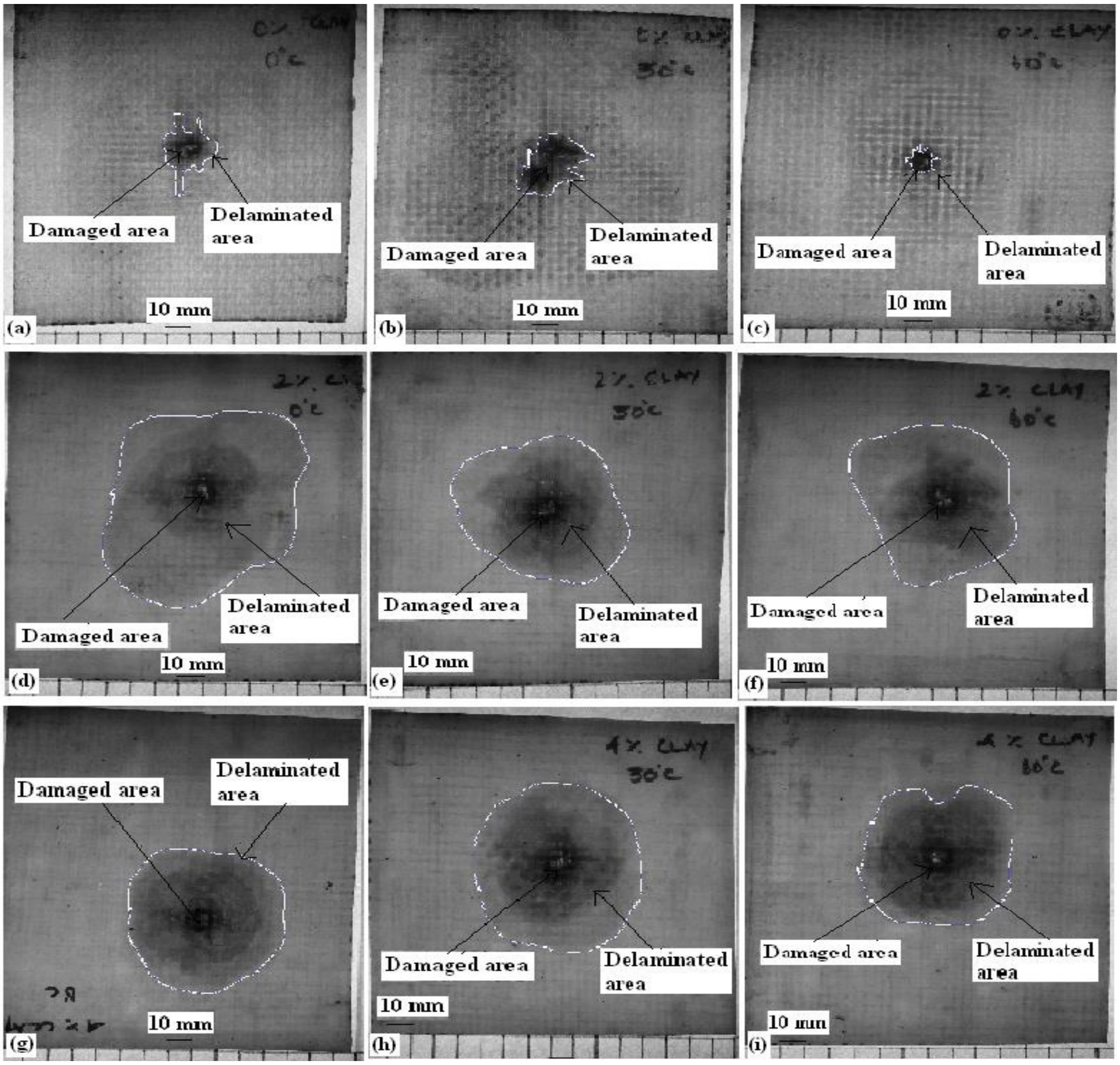

Figure 7: Laminates without clay, with 2% and 4% clay tested for projectile velocity 140 m/s at 0°C, 30° C and 60° C

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