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Damping characteristics of nanoclay filled hybrid laminates during medium velocity impact

T.P. Mohan [a], R. Velmurugan [b], K. Kanny [a, *]

[a] Composites Research Group, Department of Mechanical Engineering, Durban University of Technology, Durban, South Africa
[b] Composites Technology Centre, Department of Aerospace Engineering, Indian Institute of Technology, Madras, India

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ABSTRACT

The objective of this paper is to study the vibrational damping characteristics during medium velocity impact of nanoclay filled glass fiber reinforced epoxy hybrid laminates. A series of laminates with varying degree of nanoclay concentration (0–5 wt.%) and fiber weight fraction (25–75 wt.%) were prepared by vacuum assisted resin infusion molding (VARIM) method. The laminates were subjected to medium velocity projectile impact using in-house built gas gun set-up and the ballistic limit of laminates series was determined. The result indicated that during impact, the laminate undergoes vibrational damping. This damping property is a function of fiber weight fraction and orientation, nanoclay concentration and nanocomposite structure. A 42% increase of ballistic limit was observed for 5 wt.% nanoclay filled hybrid (50 wt.% fiber) when compared with unfilled composite. Structural and modal analysis of hybrids showed that the increased ballistic limit of nanoclay filled hybrids is due to the nanocomposite structure and improved damping and fracture properties.

1. Introduction

Fiber reinforced composites have been extensively used in aerospace industries due to their high strength-to-weight ratio when compared with their metallic counterparts [1,2]. Also the composites used in aircraft structures have to withstand sudden impact loading, which occurs in the form of projectile, bird striking, debris or tool drop. Generally, this kind of impact will be in medium velocity range (40–250 m/s) [3–5]. The study of medium velocity impact of composites is a complex subject as it involves various parameters of analysis. Commonly used parameters for medium velocity impact are the type of matrix and fibers, volume fraction, fiber architecture and its orientation in matrix, impact range, damage mechanics and energy absorption. The geometry and type of projectiles were also considered. Extensive researches were carried out with these parameters by several authors [6–12].

In recent past, hybrid composites were being developed and much of attention is focused on this type of material due to their superior thermal and mechanical properties over conventional composite. Hybrid composites consist of more than one type of reinforcement or matrix. Commonly used hybrids are carbon – aramid fibers reinforced epoxy composites (for the combined strength and impact resistance) [13], glass – carbon fibers reinforced epoxy (for a high strength with reasonable cost) [14] and carbon nanotubes (CNTs)/nanoclays filled epoxy fiber reinforced epoxy composites (for high modulus, fiber–matrix interface and thermo-mechanical properties) [15]. Special emphasizes were given to nanoparticle (CNT/nanoclay) filled fiber reinforced composites as dramatic improvement in mechanical and thermal properties were observed at very low nanoparticle concentration (at ~ 5 wt.% loading) in polymeric matrix [16–19].

However, the study on medium velocity impact of nanoparticle filled hybrid composites is very much limited. Very few studies have been carried out, for instance, Balaganesan et al. [20] have carried detailed analysis on energy absorption characteristics during medium velocity impact of nanoclay filled glass fiber reinforced epoxy hybrids and observed that the nanoclay addition in epoxy-glass fiber composite increases the ballistic limits due to increased energy absorption mechanisms. The energy absorption of matrix, nanoclay filled matrix and epoxy-fiber composites were studied in detail. It was observed that during impact, the laminate undergoes vibration but further analysis was not carried out. Chandradass et al. [21] have carried modal analysis of nanoclay filled glass fiber reinforced epoxy hybrids and found that nanoclay

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[*] Corresponding author. Tel.: +27 313732230; fax: +27 313732139.
E-mail address: kannyk@dut.ac.za (K. Kanny).

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addition increases the natural frequency of the composite. Shi et al. [22] has carried tensile, flexural, compressive and shear properties of hybrids and observed that the nanoclay addition increased these properties but with the function of clay concentration. They observed maximum increase of these properties at 2–3 wt.% nanoclay and with decreasing trend above 3 wt.% nanoclay content in hybrids. They also observed slight reduction in impact strength with the function of nanoclay content. However, suggested that the property can be improved with better dispersion of nanoclay particles in the polymeric matrix. Zerda and Lesser [23] have observed modulus increase with reduction in strength of nanoclay filled hybrid series. Improved thermal and fracture properties were also observed in nanoclay filled hybrids [24,25]. It has been also observed that the nanoclay filled epoxy-glass fiber hybrids is strain rate sensitive [26,27]. Even at a low range of an increase of strain rate from 0.0001 to 0.1 s^{-1}, the longitudinal strength and modulus were increased by about 15% [28].

From the literature, it was observed that the effect of nanocomposite structures, nanoclay concentration and damping properties during impact had not been studied in detail. The objective of this paper is to study this effect during medium velocity impact in nanoclay filled epoxy-glass fiber reinforced hybrid laminates. To carry out this study, nanoclay filled (0–5 wt.%) and glass fiber reinforced (with various fiber weight fraction and orientation) epoxy laminates were subjected to medium velocity impact and the ballistic limits of hybrid series were determined. The damping and fracture behavior of hybrids during impact were also studied and discussed. The result showed that the improved ballistic limit of nanoclay filled hybrids is due to the increased damping and failure mechanisms.

2. Experimental details

2.1. Raw materials

Diglycidyl ether of bisphenol-A (DGEBA) based epoxy resin supplied with the trade name of LR-20 was used as the matrix material. The curing agent was unmodified cyclic aliphatic amine based epoxy hardener supplied with the trade name of LH-281. Silane treated E type plain glass woven roving (450 GSM) was used as the primary reinforcement. All these materials were purchased from AMT Composites, Durban, South Africa. The secondary reinforcement nanoclay filler supplied under the trade name Cloisite-30B was obtained from Southern Clay Products Inc., USA. Cloisite 30B is an organically modified MMT clay with MT2EtOH based tallow compound, where MT2EtOH is methyl tallow bis-2-hydroxyethyl quaternary ammonium compound.

2.2. Laminate preparation

Glass fiber reinforced, and nanoclay filled epoxy hybrid laminates (with various fiber and nanoclay weight fraction) were prepared by vacuum assisted resin infusion molding (VARIM) process. Laminate processing involved two steps and is shown in Fig. 1: the first step was mixing of nanoclays in the epoxy resin, and the second step was the infusion of the modified resin into the glass fiber rovings.

In the first step, six (6) layers of plain weave glass fiber (WGF) rovings were cut to size 35 cm × 35 cm and subsequently weighed. Three different weight fraction of epoxy resin was used corresponding to the weight of 6 layers WGF. The fiber weight fraction of 0.25, 0.5 and 0.75 were chosen in composite. In each fiber weight fraction composite series, nanoclays of various weight percentages (0–5 wt.%) to epoxy/hardener mixture was taken and infused in glass fibers. Initial mixing of epoxy resin and nanoclay was carried out at 70 °C for 1 h at 500 rpm with temperature controlled magnetic stirrer. The mixing was very efficient at the high temperature due to less viscosity of epoxy resin and high shear force. After mixing the resin with the clay, the epoxy resin–clay solution was cooled to room temperature and then 30 wt.% hardener (equivalent to epoxy resin weight) was added to the epoxy–clay mixture and followed by laminate processing. The second step was the vacuum infusion of resin to form laminates. The laminates (6 layers WGF) were processed at 2 bar vacuum pressure. The resin infused laminate is set to cure for 24 h at room temperature and then removed from vacuum bag molding. The testing and characterization of laminates were performed after 7 days.

2.3. Characterization and testing

The structure of the composites was examined by X-ray diffraction (XRD) and Transmission electron microscopy (TEM) analysis. Philips PW1050 diffractometer was used to obtain the X-ray diffraction patterns of nanoclay and laminate series using CuKα lines ($\lambda = 1.5406$ Å). The diffractrograms were scanned up to 16° (2θ) in steps of 0.02° with a scanning rate of 0.5°/min. Microscopic investigation of selected laminate specimens was conducted using a Philips CM120 TEM with an operating voltage of 120 kV.

The ballistic test on laminates was conducted by an in-house built gas gun set-up [20] and the schematic sequence of impact and damping measurement is shown in Fig. 2. The gas gun set-up consists of a cylindrical chamber in which compressed air was used to propel the projectile. The pressure regulator and solenoid valve were used to control the pressure within the chamber. The velocity of projectile was controlled by changing the gas pressure within the chamber. A standard cylindrical steel projectile with mass of 11.8 g was used to impact the laminates at 1 m distance. Three laminates of each series were subjected to medium velocity projectile impact with various velocity ranges (40–150 m/s) using cylindrical projectile. The ballistic limit of the unfilled and nanoclay filled laminates series was determined by measuring the speed of projectile sufficient to pierce and pass through the laminate. The speed of the projectile was measured by Phantom V611 high speed camera (video and image recorder). The distance covered (reference distance Point A and B) by projectile was measured using a horizontally attached measuring scale (Fig. 2 of camera image), while the time for projectile to pass points A and B is displayed in high speed camera video recorded. The ratio of distance (point A to B) to time will measure speed of the projectile. The camera has features of 640 × 480 pixels resolution, 18,000 frame/s and exposure level of 32 μs with Nicon 50 mm focal length. The captured image/video were processed in PC using Phantom inbuilt PCC2-1 software version.

NI accelerometer was attached at rear side of the laminate to record the vibration and damping during projectile impact. The time vs amplitude (mV) curves were generated in PC using NI PXI-1042 (DAQ) attached software. The natural frequency (f_n) and damping factor (ζ) of the laminate series were determined using Fast Fourier Transform (FFT) method. To study the effect of fiber orientation on impact and vibration of laminate, the fiber direction in laminate was oriented to 0°/90°, 15°/105°, 45°/135° and 60°/150° with respect to the perpendicular direction of projectile impact.

The fracture surface analysis of projectile impact laminates was analyzed using Zeiss Scanning electron microscopy (SEM) modal EVO HD 15 operating at 20 kV. The strain energy release rate G_{IIc} of laminate series is calculated from the three point bending test of end notched flexural (ENF) specimen using MTS-UTM machine. Equation (1) is used to predict the values for hybrid laminate