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ORIGINAL PAPER

Nanoclay Addition and Core Materials Effect on Impact and Damage Tolerance Capability of Glass Fiber Skin Sandwich Laminates

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Abstract This study explores the effects of modified (OMMT) nanoclay and core material on low velocity impact behavior and damage tolerance capability of glass fiber reinforced (FRP) polyester resin – polystyrene foam (PS) sandwich laminates. The FRP and sandwich laminates are prepared by a compression molding technique for investigation. Low velocity impacts are carried out on all the fabricated laminates by using a instrumented drop weight impact tower with the energy level of 30 J and load–energy–time plots were recorded using data acquisition software. Post impact flexural tests have been conducted to evaluate the damage tolerance capability of the fabricated composite laminates. X-ray Diffraction (XRD) results have been obtained for the samples, where the nanoclay has indicated that intergallery spacing of the layered clay increases with the matrix. Scanning Electron Microscopy (SEM) has given the morphological picture of the nanoclay dispersion in the polymer fracture samples. The results of the study show that the impact properties and damage tolerance capability of the 4% nanoclay polyester sandwich have been greatly increased.

Keywords Nanoclay · Sandwich laminates · Impact behaviour · Post impact flexural · Nanoclay · Damage tolerance

1 Introduction

In recent years, there has been a keen interest in making the composites of glass fibers reinforced polymer sandwich laminates with low density core materials. These sandwich composite materials provide high stiffness, strength and light weight which make them an attractive material for primary load bearing applications. The properties of composites are significantly related to the properties of composite constituents, i.e., fiber, matrix and the interphase between fiber and matrix [1].

The utilization of nanoclay as filler in polymers has attracted considerable attention of researchers due to the improved static, dynamic, thermal, flame retardant and gas barrier properties of the resulting composites [2–6]. Incorporation of nano-particles (clays, carbon nanotubes, etc.) in the matrix system for fiber reinforced composites has been recently studied by several groups [7, 8] to improve the static and the dynamic properties. Avila et al. [9] have investigated the influence of montmorillonite (MMT) silicate layers on glass-fiber-epoxy laminated composites behavior by low-velocity impact and X-ray diffraction tests. The results have shown that, for the four edges clamped condition not only the delamination phenomenon is reduced, but also the damping is increased during the rebounds. Anbusagar et al. [10] have investigated the influence of nanoclay content on sandwich composites under flexural and impact loading. Four different combinations of sandwich composite panels have been made of fiber glass/nano-modified polyester face sheets and jute core prepared by a

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Hand lay-up manufacturing technique (HL). The measurements show that the flexural and impact properties have greatly increased over the range of nanoclay loading.

Hosur et al. [11] have fabricated sandwich panels with neat and nanophased foam core along with three-layered plain weave carbon fabric/Sc-15 epoxy composite face sheets and have tested them under the low velocity impact test. Test results demonstrate that the samples with nanophased foam have sustained higher loads and also have lower damage areas when compared with neat counterparts. Nanophased foam cores have exhibited relatively more brittle fracture. The effect of a nanoclay enhanced epoxy matrix on Kevlar composites laminates under the low velocity impact were studied by Reis et al. [12]. The laminates which were manufactured with epoxy resin and were filled with 6% of nanoclay show the best performance in terms of elastic recuperation and penetration threshold. Ávila et al. [13] have investigated the influence of exfoliated nano-structures on sandwich composites which are made of fiberglass/nano-modified epoxy face sheets with polystyrene foam cores under impact loadings. The results show that the addition of 5% of nanoclay leads to more efficient energy absorption. The failure modes have also been affected by the nanoclay addition to face sheets. Anbusagar et al. [14] have investigated the effect of nanoclay modified polyester resin on flexural, impact, hardness and water absorption properties of untreated woven jute and glass fabric hybrid sandwich laminates experimentally. The test results have indicated that the flexural properties have been greatly increased at 4% of nanoclay loading while impact, hardness and water absorption properties have increased at 6% of nanoclay loading. Sarasini et al. [15] have investigated the low velocity impact behavior of E-glass/basalt reinforced hybrid laminates, manufactured by a resin transfer molding technique. Their results showed that the basalt and hybrid laminates with an intercalated configuration exhibited higher impact energy absorption capacity than glass laminates, and enhanced damage tolerance capability. From the above literature it is observed that information on low-velocity impact on laminated composites is in adequate supply; it deals more with single fiber and hybrid composites reinforced with various fibers such as glass, Kevlar, carbon, graphite etc. Moreover, to the best of the our knowledge, there have been no studies reported in the open literature about the impact response and relative comparison of FRP and nano-polymer FRP sandwich laminate composites, which are very important for actual application of this material.

From the analysis of the above, the objective of this paper is to study the low-velocity impact response and damage tolerance capability of a polymer-nanoclay-fiber-glass nanostructured sandwich laminate by conducting flexural tests on impacted and non-impacted composite laminates. These objectives are met by conducting the various studies for which the clay/polyester nanocomposite systems are prepared to use as matrix material for the fabrication of glass fiber reinforced sandwich composite laminates with polystyrene foam core. The structures of clay and clay-containing composites have been investigated by X-ray diffraction (XRD) and Scanning Electron Microscopy (SEM). Pre- and post-impact behavior of sandwich laminates have been investigated under low velocity impact and post-impact flexural load respectively.

2 Materials and Experimental Procedure

2.1 Materials and Preparation of Nano-Composites

The plain weave glass fabric 600 g/m^2 supplied by Binani industries limited, Mumbai, India has been used as reinforcing material for the preparation of glass and sandwich laminates. Isophthalic polyester is used as the resin. Methyl ethyl ketone peroxide and cobalt naphthanate are used as catalyst and accelerator respectively. The core used for sandwich laminates is closed-cell PS foam (Styrofoam). This foam has a density of 60 kg/m^3. The core was 8 mm thick. The commercial nanoclay used in this study is provided by Southern Clay Products, Na^+ montmorillonite (unmodified having CEC 92.6 meq/100 g clay) which is also modified to obtain organically modified montmorillonite (OMMT).

Nano-modified polyester resin is developed by using a sonicator mixer (Fig. 1a). A suitable amount of modified nanoclay is dispersed into the polyester resin to obtain a nano-modified polyester resin of concentration 2, 4 and 6 wt%. The polyester and nanoclay mixture is mixed with a sonicator mixer for 30 min for each group of polymer matrices. After that a suitable amount of curing agent is added to the polyester resin/nanoclay mixture and mixed for an additional 5 min. The nano-dispersed prepolymer is allowed to rest to remove air bubbles, and is set aside for hand layup processing. The mixture of nanoclay and polyester resin is applied over the fiber mat of 300 cm square and rolled for removal of air gaps (Fig. 1b). Then the wet laminate is placed in the compression molding machine for curing and proper lamination (Fig. 1c). The final glass and sandwich laminates are a square plate of 300 × 300 mm dimensions with an overall thickness of 4 mm and 10 mm respectively (Fig. 1d and e). After that, the samples with dimensions of 125 mm × 125 mm for the mechanical characterizations have been cut from 300 mm wide square FRP and sandwich composite laminates (Fig. 1f). The preparation of nano-modified polyester resin is presented in Fig. 1. All the laminates are processed at a total fiber volume fraction

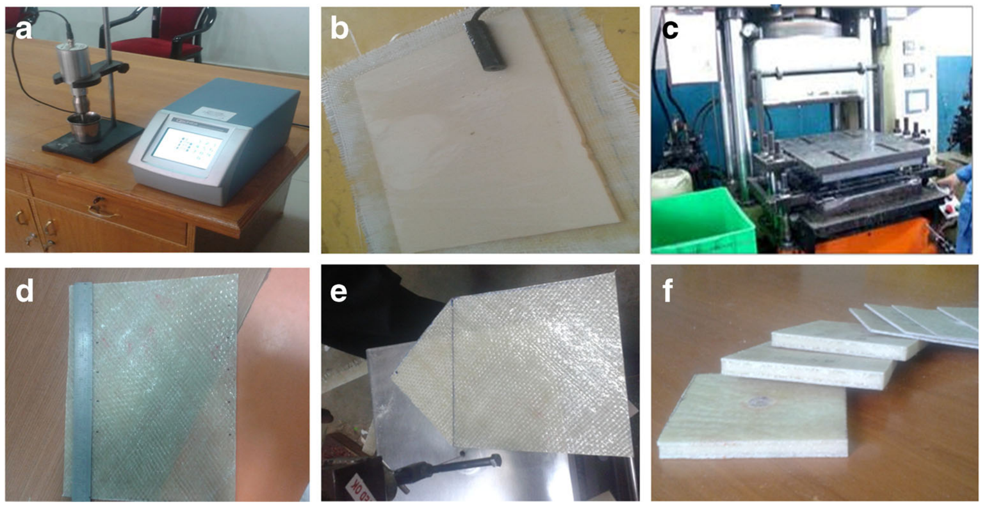

Fig. 1 **a–f** Preparation of nano-composite laminates **a** mixing of nanoclay **b** lamination of composites **c** compression molding **d** marking of laminates **e** cutting of laminates **f** various laminates samples fabricated

of 33%. The total fiber volume fraction is calculated using Eq. 1 [16].

$$V_f = \frac{(W_g / \rho_g)}{(W_g / \rho_g) + (W_r / \rho_r)} \quad (1)$$

Where W_g, and W_r are the weights of the glass and resin, respectively, and ρ_g, and ρ_r are the densities of the glass and resin respectively.

2.2 Characterization

2.2.1 Low Velocity Impact Testing

Low velocity impact tests have been carried out using an instrumented drop weight impact test system (DYNATUP 8250) with the dimensions previously described. The drop weight impact tower consists of a crosshead with variable weight arrangement, a mechanical single impact bounce brake to prevent several impacts, sample support fixture, and velocity detector assemblage. The impact samples were divided into six groups with three samples in each group and tested for 30 J of energy. The samples were clamped on all four sides in the supporting fixture with a clear span of (125 × 125). The impact machine was operated in gravity mode with constant impactor mass of 2.59 kg which is equal to the sum of the main mass (2.29 kg) and tup mass (0.3 kg). Impact data were collected by a hemispherical tub (load cell) of 12.7 mm diameter and velocity detector connected directly to the data system. The data system generates force–time, energy–time and force–deflection plots which can be subsequently displayed on the computer monitor, along with the computed values of input energy, impact velocity, peak load, total energy, energy at peak load, etc.

2.2.2 Pre- and Post-Impact Flexural Testing

The pre- and post–impact flexural tests have been conducted in order to determine the degradation in flexural strength and stiffness and retention of flexural load carrying ability of the FRP and sandwich composite laminates. Four-point bending tests were performed on three samples for each configuration in accordance with ASTM D 6272. The test

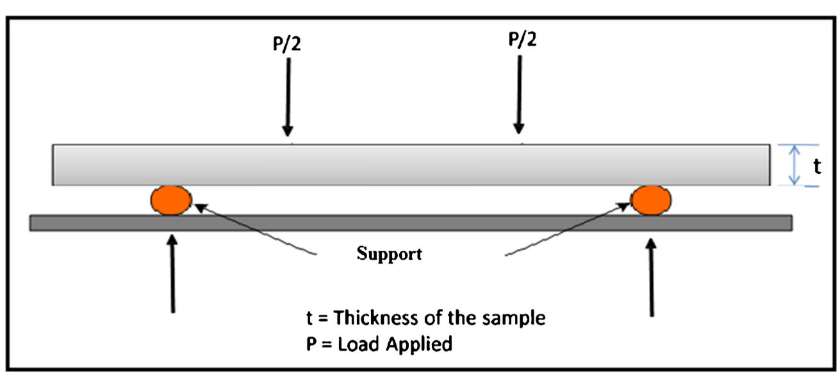

Fig. 2 Four point bending load arrangement for FRP and sandwich sample

configuration of four-point bending is shown in Fig. 2. A span-to-depth ratio of 16:1 and a cross-head speed of 2.5 mm/min were used. The samples for post–impact flexural tests were cut from the squared impacted samples to a size of (125 × 15) mm, such that the damage zone is oriented at the center of the flexural test samples, as shown in Fig. 3. Note that the damage extension developed by an impact energy of 30 J does not exceeding the sample width as considered per the ASTM standard.

2.2.3 Microstructural Characterization

Samples with and without nanoclay particles are obtained from laminates manufactured with different concentrations (0, 2, 4 and 6 wt%) and they are analyzed by the X-ray diffraction (XRD) technique by using Rigaku smart lab-9 kW, with Cu Kα radiation. The samples are scanned in the interval of $2\theta = 0 - 15$ at 40 kV and 30 mA. Using XRD, the dispersion behavior of clay particles loaded to the matrix with different concentration is analyzed.

Scanning Electron Microscopy is utilized to analyze the dispersion of clay in the nanocomposites. All the samples are examined with a Carl Zeiss high resolution microscope at 500X magnification. In addition to the polished surfaces, the fractured surfaces of the mechanically tested samples were also studied by SEM to identify any change in adhesion between the matrix and glass fibers because of the nanoclay.

3 Results and Discussion

3.1 Analysis of Impact Test Results

Figures 4 and 5 show the typical load and energy versus time responses for all six kinds of samples at an incidental impact energy of 30 J, respectively. These curves can provide a complete interpretation of the damage initiation and growth, as well as changes of the samples stiffness [17].

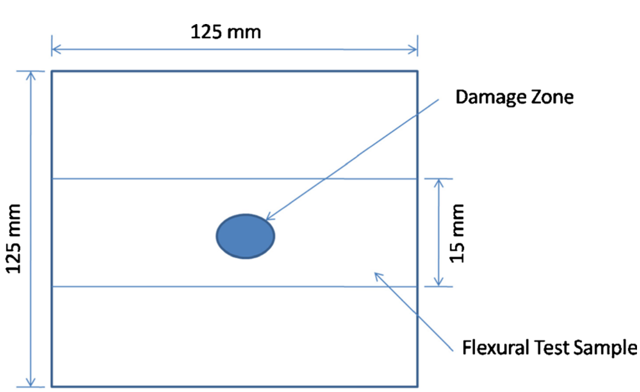

Fig. 3 Preparation of post-impact flexural test sample

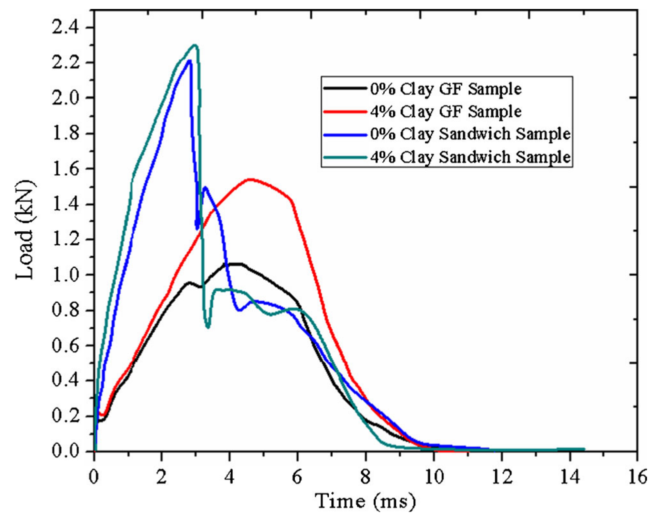

Fig. 4 Typical load vs. time response curves of various samples

Table 1 summarizes low velocity impact test results of FRP and sandwich laminates. The first sudden load drop in the load vs. time plot is a sign of internal delamination beginning or fiber-matrix interface failure in the laminates close to the back surface of the impacted laminates [18]. This load point is called the incipient damage point and has an insignificant effect on the load carrying ability of the laminates. The equivalent energy is called incipient energy. However, as the impact continues, there are noticeably different trends for different composite laminates (see Fig. 4). The load decreased suddenly after reaching the peak level.

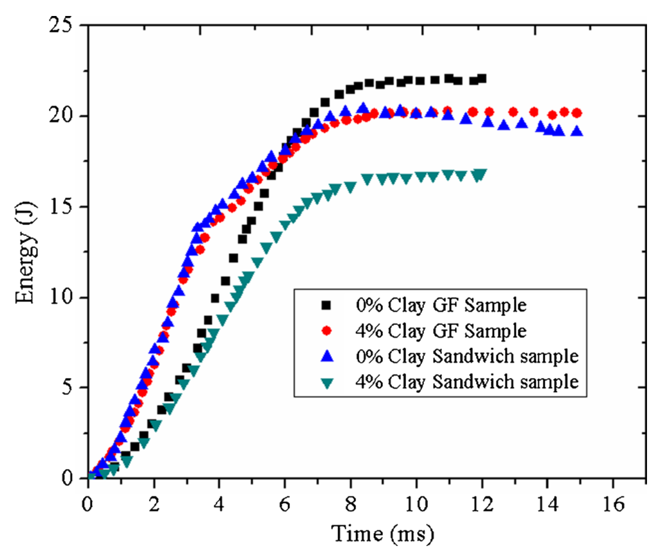

Fig. 5 Typical energy vs. time response curves of various samples

Table 1 Parameters obtained from low velocity impact test for FRP and sandwich laminates samples impacted at 30 J

Samples	Peak load (N)	Absorbed energy (J)	Displacement (mm)	Damage (degree)	Damage area (mm^2)
G0	1.10	22.33	12.32	0.74	1036.65
G2	1.42	18.23	11.08	0.60	800.28
G4	1.56	17.23	10.05	0.57	600.98
G6	1.46	19.70	11.33	0.65	728.20
S0	2.31	7.58	7.89	0.25	–
S4	2.36	7.39	7.56	0.24	–

Further, damage propagates from the back face (bottom side) on to the front face (top side) until the maximum load point is reached. This result has also been established in Ref. [19]. They recommended that the tendency could be recognized to be critical structure damage. Then there is a load redeployment of the existing composite laminates is carried out until the impact load is detached. Maximum load point is the peak value of the load which the material can tolerate under a particular impact event, before undergoing foremost damage.

The average value of peak loads computed at 30 J energy levels is plotted for different laminate samples as shown in Fig. 6. It is noticed that the addition of nanoclay by 2 and 4 wt%, results in the increase in peak load. This increase is due to greater stiffness and load carrying ability of the nanoclay reinforcing the polymer system [20]. However, further addition of nanoclay results in the decrease of peak load. This may be due to the existence of a saturation limit of the polyester resin system. Once the saturation limit is reached, the additional nanoclay dispersed into the matrix precipitates in the form of immiscible nanostructures, which can be sources of cracks nucleation, as they are stress absorption hot spots [9]. This hypothesis can be corroborated by the XRD tests, where a significant increase on diffracted energy has been noticed. Also it is noticed that a higher diffracted energy is a sign of greater entropy. This increase in entropy can be caused by this precipitated third phase. This hypothesis has been confirmed by SEM images of the fracture surface of the 6% nanoclay loaded sample (Fig. 19f). From the low velocity impact behavior of FRP samples, it is noticed that the peak load starts decreasing after 4 wt% of nanoclay loading. Hence, for the analysis of sandwich laminates only 0 and 4% nanoclay sandwich laminates are fabricated and studied. The

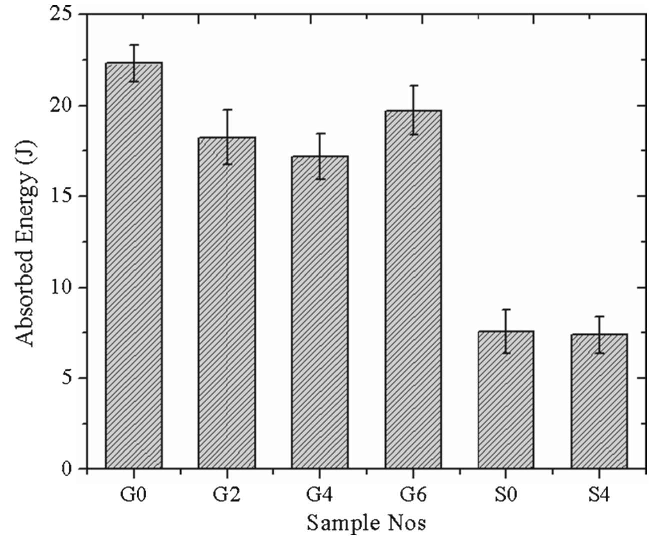

Fig. 7 Absorbed energies of various laminate samples

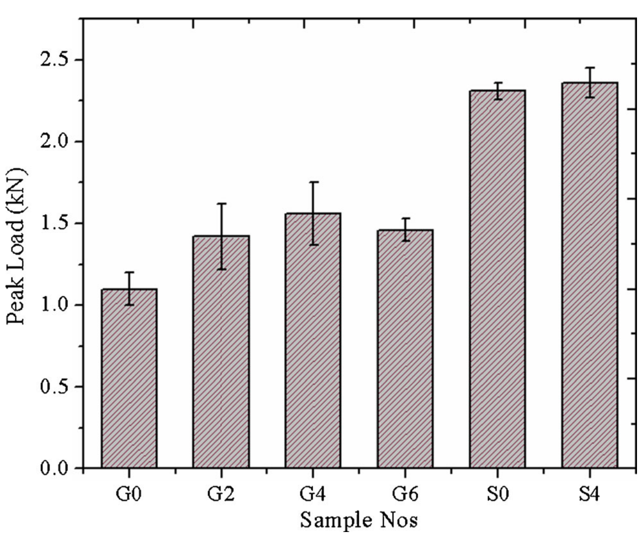

Fig. 6 Peak load of various laminate samples

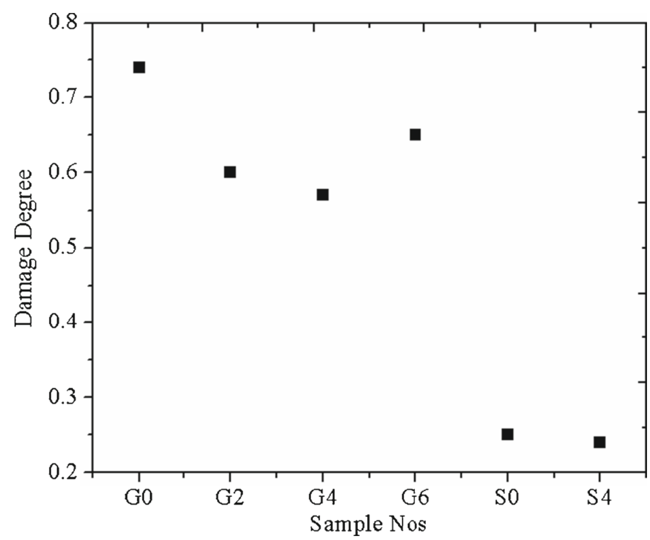

Fig. 8 Damage degree of various laminate samples

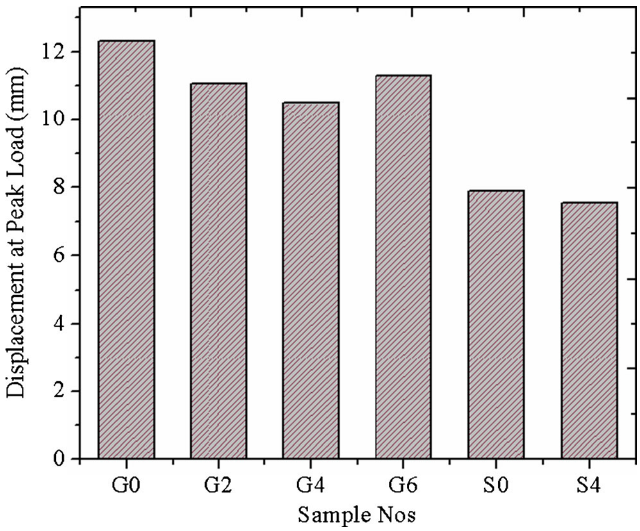

Fig. 9 Displacement at peak load of various laminate samples

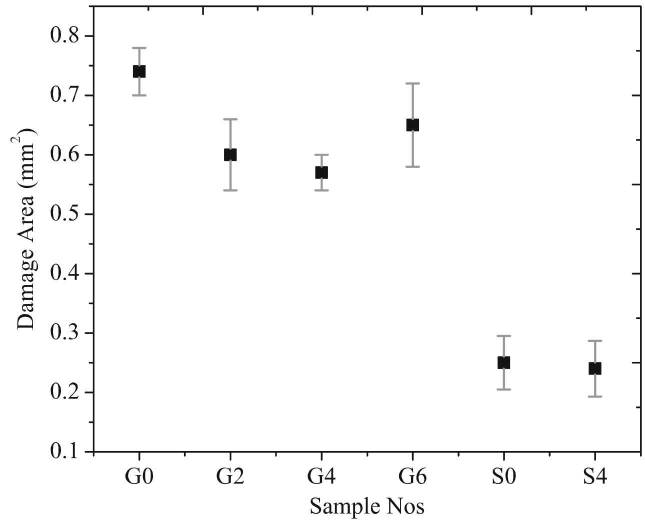

Fig. 11 Damage area of various laminate samples

sandwich laminate S4 is found to have the highest load carrying ability and can resist 114% more load at 30 J when compared to the load carrying ability of 0% nanoclay FRP laminate (G0), at the same energy level.

In the energy-time response diagram the energy equivalent to the point when the load curve reaches zero load level is the total energy absorbed by the laminate. Figure 7 shows the total energy absorbed for 30 J incident energy levels for different laminate samples. The figure reveals that the total energy absorbed is the maximum for the 0% nanoclay FRP (G0) laminate. The total energy absorbed by the laminate decreases with the increase in the nanoclay content up to 4% by weight, beyond which it increases slightly. The sandwich laminate S4 has the lowest energy absorption capacity at a given energy level. In order to evaluate the damage accumulation, several parameters have been considered [21–23]. Figure 8 shows the so-called damage degree, which is defined as the ratio between the energy absorbed and the energy of impact [24] which is less than one up to incursion and equal to one when it occurs. In the tested laminates, this parameter decreases with increasing nanoclay loading, reaching a minimum value of 0.24 for the S4 sample, suggesting that it can take a higher amount of the impact energy to reach the maximum value. This confirms the effectiveness of the sandwich effect and nanoclay loading of FRP laminates to improve the impact behavior.

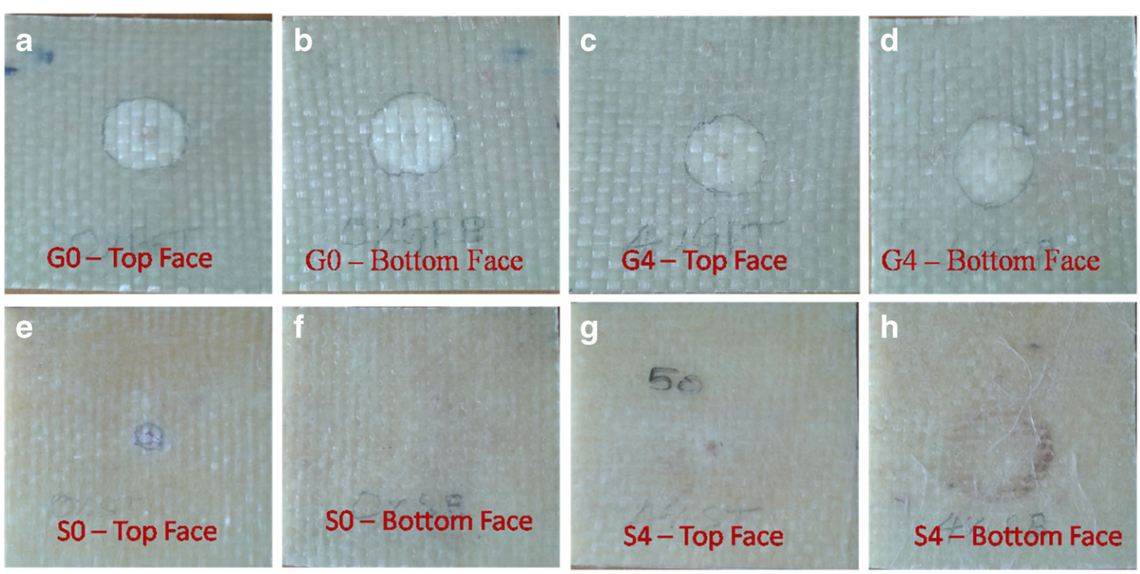

Fig. 10 **a**–**h** Damage pattern of various laminate samples

Table 2 Summary of flexural properties of FRP and sandwich laminate samples

Samples	Non-impacted samples			Impacted samples			Normalized flexural properties	
	Strength (MPa)	Stiffness X 10^3(N-mm^2)	Stiffness ratio	Strength (MPa)	Stiffness X 10^3(N-mm^2)	Stiffness ratio	Strength ratio	Stiffness ratio
G0	101.13	390.42	1	72.45	268.40	1	0.71	0.68
G2	100.21	404.48	1.03	74.28	298.81	1.11	0.74	0.73
G4	125.45	615.68	1.56	102.42	490.38	1.82	0.81	0.79
G6	120.56	508.16	1.38	94.2	395.84	1.47	0.78	0.77
S0	119.05	5124.78	13.47	102.68	4500.28	16.79	0.85	0.87
S4	127.67	8517.67	21.49	106.29	8102.58	30.31	0.88	0.95

The deflection of the composite laminate at maximum load in a low velocity drop impact test depends mainly on the stiffness and thickness of the laminate and also on the incident impact energy. Figure 9 shows deflection at maximum load for 30 J incident energy levels for different laminate samples. From Fig. 9 it is noticed that the maximum deflection decreases with the increase in nanoclay content up to 4 wt%. Further addition of nanoclay resulted in an increase in the maximum deflection. The decrease in the deflection up to 4% nanoclay is due to greater stiffness gained by the sandwich effect and nanoclay loading in the polymer matrix. The sandwich laminate S4 found to have the lowest deflection at maximum load of 39% when compared to the 0% nanoclay FRP laminate (G0), at the same energy level.

3.2 Analysis of Damage Pattern and Damage Area

Damage observed on FRP and sandwich laminates caused by the tub impact can be classified in four categories: (i) barely visible damage with matrix cracks and surface dent; (ii) barely visible damage without matrix cracks and surface dent; (iii) barely visible damage (iv) no visible damage. Figure 10a–h shows each one of these categories, which are impacted at an energy level of 30 J. For the G0 sample the main damage mode is detected as category (i) (barely visible damage with matrix cracks and surface dent) which is shown in Fig. 10a. For the G2 sample the main damage mode is detected as category (ii) (barely visible damage without matrix cracks and surface dent) which is shown in Fig. 10b. The damage modes for samples G4 and G6 are detected as barely visible damage while no visible damage is found for sandwich samples (S0 & S4). The conclusion is consistent with the results of Fig. 6. That is the inflection points on the equivalent load–time curves suggest the damage generation and propagation [17]. From the above results, it can be observed that the 4% nanoclay modified FRP skin sandwich laminate samples are superior to other laminate samples, in terms of energy absorbed and impact resistance. The nanoclay in polyester resin samples reinforces the system in the thickness direction, thus effectively preventing a surface dent from occurring. Since the 4% nanoclay modified FRP skin sandwich laminate samples showed higher performance in impact resistance as compared to other laminates, further study is expected to optimize the energy dissipation, and damage accumulation by applying a wider range of impact force.

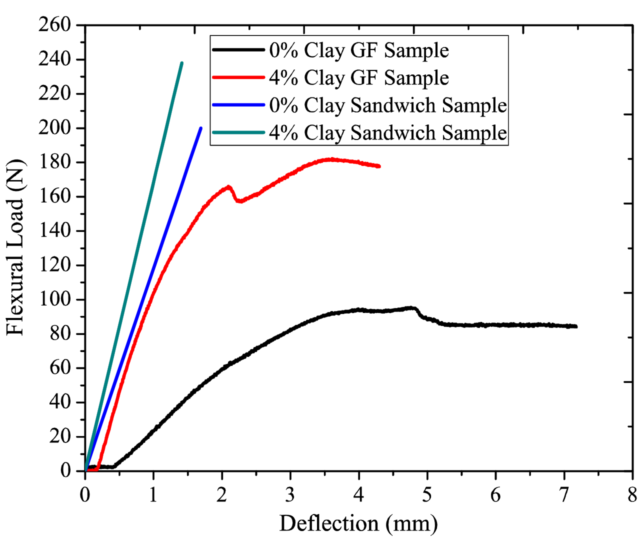

Fig. 12 Typical flexural load – deflection curve of non-impacted FRP and sandwich laminate samples

The visual observations of impacted FRP laminate samples reveal that the damage area decreases with an increase in to 4% nanoclay loading. The damage pattern for FRP laminates is more or less circular on the top face and bottom face. The matrix crack length decreases with an increase in the nanoclay in the polymer matrix system, which is seen in 4% of nanoclay FRP laminate samples. The damage areas are estimated from direct photo images of the sample which is impacted at an energy level of 30 J by performing a series of at least 10 measurements of the front and back damaged areas. The plot of damage area for different FRP laminate samples is shown in Fig. 11 with average values and their

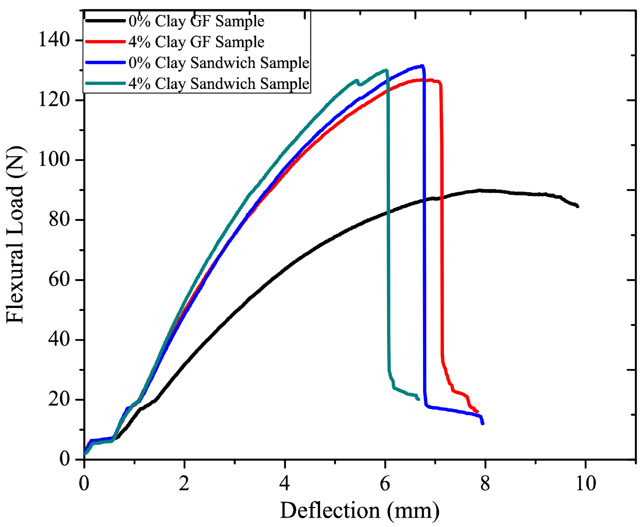

Fig. 13 Typical flexural load – deflection curve of impacted FRP and sandwich laminate samples

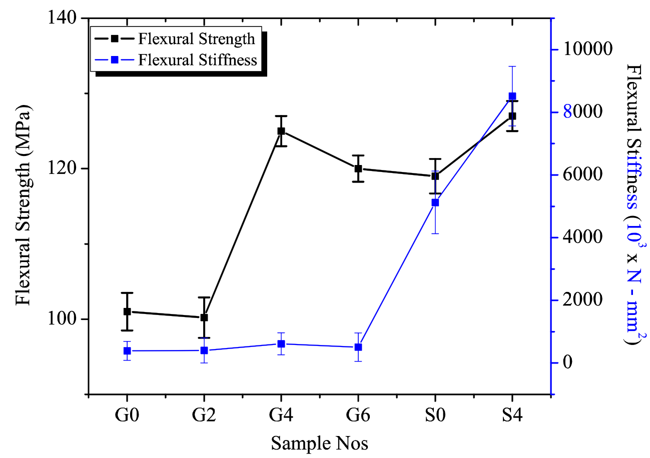

Fig. 15 Flexural properties of various non-impacted laminate samples

standard deviation. A linear decreasing trend in the damage area is noticed with an increase in the nanoclay for all types of FRP laminates. For 0% nanoclay FRP laminates (G0), the damage area is 1036.6 mm^2. For 4% nanoclay FRP laminate (G4), the damage area is are 600.98 mm^2. The damage area of 4% nanoclay laminate is reduced to about 42%. From Fig. 11 it is possible to conclude that the samples with 4% nanoclay content are the ones with the best performance with respect to damping hence they are able to reduce the damage area with more efficiency. Notice that during impact, the only sample where no surface dent and matrix cracks are noticed is the one with 4% nanoclay FRP skin sandwich laminate samples (S4). In fact, small numbers of rebounds are even absorbed.

3.3 Analysis of Pre- and Post-Impact Flexural Test Results

The evaluation of the residual strength of a damaged structure is of practical importance for an effective damage tolerant design. It is well known that impact-damaged laminates experience significant strength reductions when subjected to bending load, compared with undamaged samples due to the local instabilities arising from the existing damage. Table 2 summarizes flexural properties of undamaged and impact damaged composites laminates while Figs. 12 and 13 show the comparison of the typical flexural load - deflection responses of undamaged and impact-damaged composite laminate samples respectively.

Figures 14 and 15 show flexural properties (flexural strength and flexural stiffness), of impacted and non-impacted samples respectively. It is observed from both impacted and non-impacted samples that the flexural properties such as flexural strength and flexural stiffness

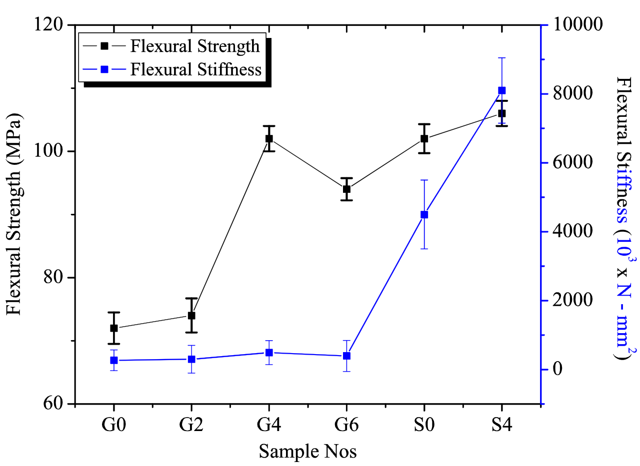

Fig. 14 Flexural properties of various impacted laminate samples

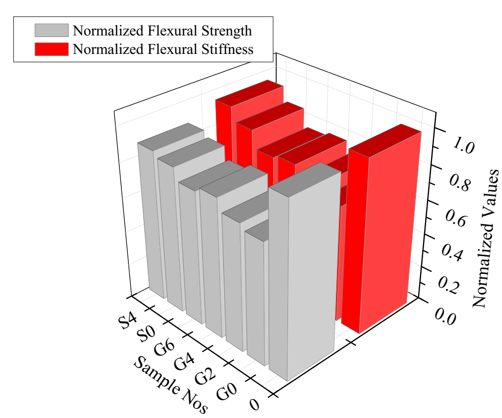

Fig. 16 Normalized flexural properties of various laminate samples

increased with increase of nanoclay loading up to 4%. Further, addition of nanoclay (6%) leads to reduction of flexural properties due to agglomeration of nanoclay in the resin. Increase in stiffness is obtained by reinforcement of nanoclay and moment of inertia of laminates by placing a soft core between GFRP skins. For better evaluation of the influence on impact damage on the residual properties, the normalized flexural properties of each sample have been calculated as the ratio between the mean flexural properties of the impacted samples and the mean flexural properties of the undamaged samples and are represented in Fig. 16 for different laminates. Further, flexural stiffness ratios for non-impacted and impacted samples have been evaluated and are presented in Fig. 17. As expected, samples with larger damaged area are matched by a reduction in normalized residual flexural properties for all laminates studied. Similar to the above observation in that the laminates containing nanoclay resulted in a smaller damaged area as indicated by the photo image measurements (Fig. 10a–h), nanoclay also gave rise to higher normalized residual flexural properties than the laminates made from neat polyester. Increase in the normalized residual flexural strength and stiffness for the 4% nanoclay sandwich sample (S4) is found to be 23 and 40% respectively, when compared with the 0% nanoclay sample (G0).

3.4 XRD Analysis

The results of the x-ray diffraction study are shown in Fig. 18 in which up to 4% nanoclay the results obtained are almost similar [20]. Samples with nanoclay particles have a d-spacing of 18.77 Å, while the d-spacing of the natural nanoclay particle is 11.7 Å. This 51% increase in the gallery spacing of the nanoclay is a clear indication of intercalation. The polyester resin molecules have penetrated between the clay sheets and have resulted in the expansion in gallery spacing. The disappearance of a peak indicates the separation of clay layers and the formation of an exfoliated nanocomposite. For the organoclay content of 6% nanoclay sample there is a broad peak at 2θ value of 4.5° and the corresponding intergallery spacing is 24.22 Å. This indicates the formation of an intercalated nanocomposite.

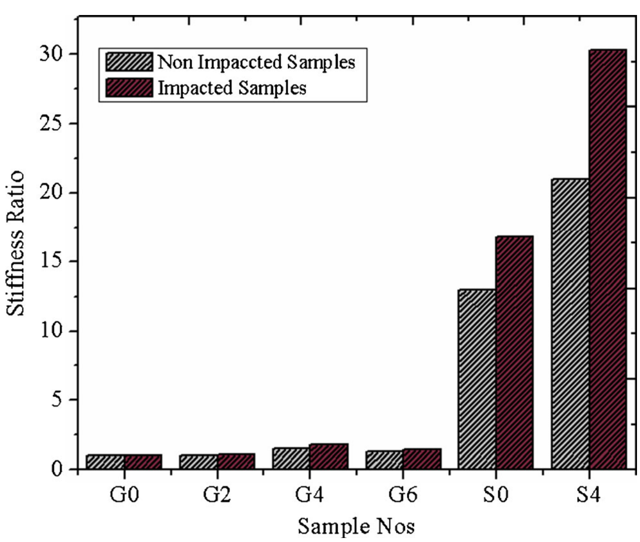

Fig. 17 Flexural stiffness ratio of various laminate samples

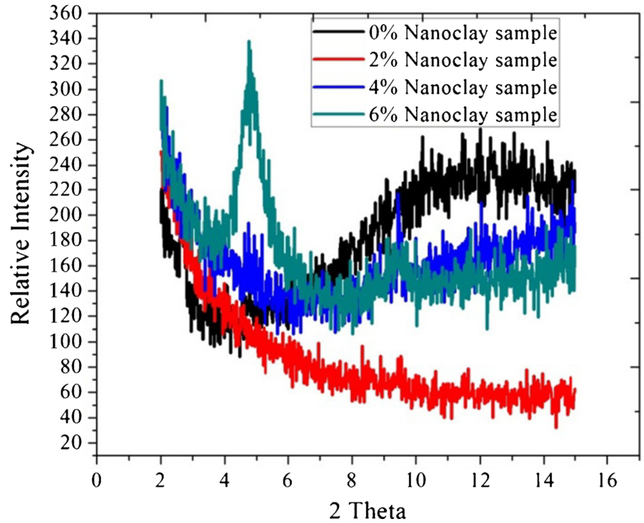

Fig. 18 X-ray diffractograms of laminate with respect to different samples

3.5 SEM Analysis

The scanning electron micrographs of before and after fracture surfaces of the composite samples are shown in Fig. 19a–f. The image observed in nanocomposite samples is an indication of the homogeneity of the nanoclay dispersion. Compared with the sample without nanoclay, samples containing 4 and 6 wt% nanoclay display a granular smooth surface topology with geometric features at smaller length scales as shown in Fig. 19c. A fiber bundle from the fracture surface of the composite sample without nanoclay is shown in Fig. 19d. Matrix residues that are observed on the fiber surfaces and between fibers show poor signs of good fiber-matrix adhesion. It is interesting to note that the fiber matrix interface contains more matrix material when compared to the sample without nanoclay. Especially the buildup of nano-modified matrix residues around the fibers is notable. Existence of nano-matrix material around the fibers after fracture indicates that effective fiber-matrix adhesion is maintained after the addition of nanoclay.

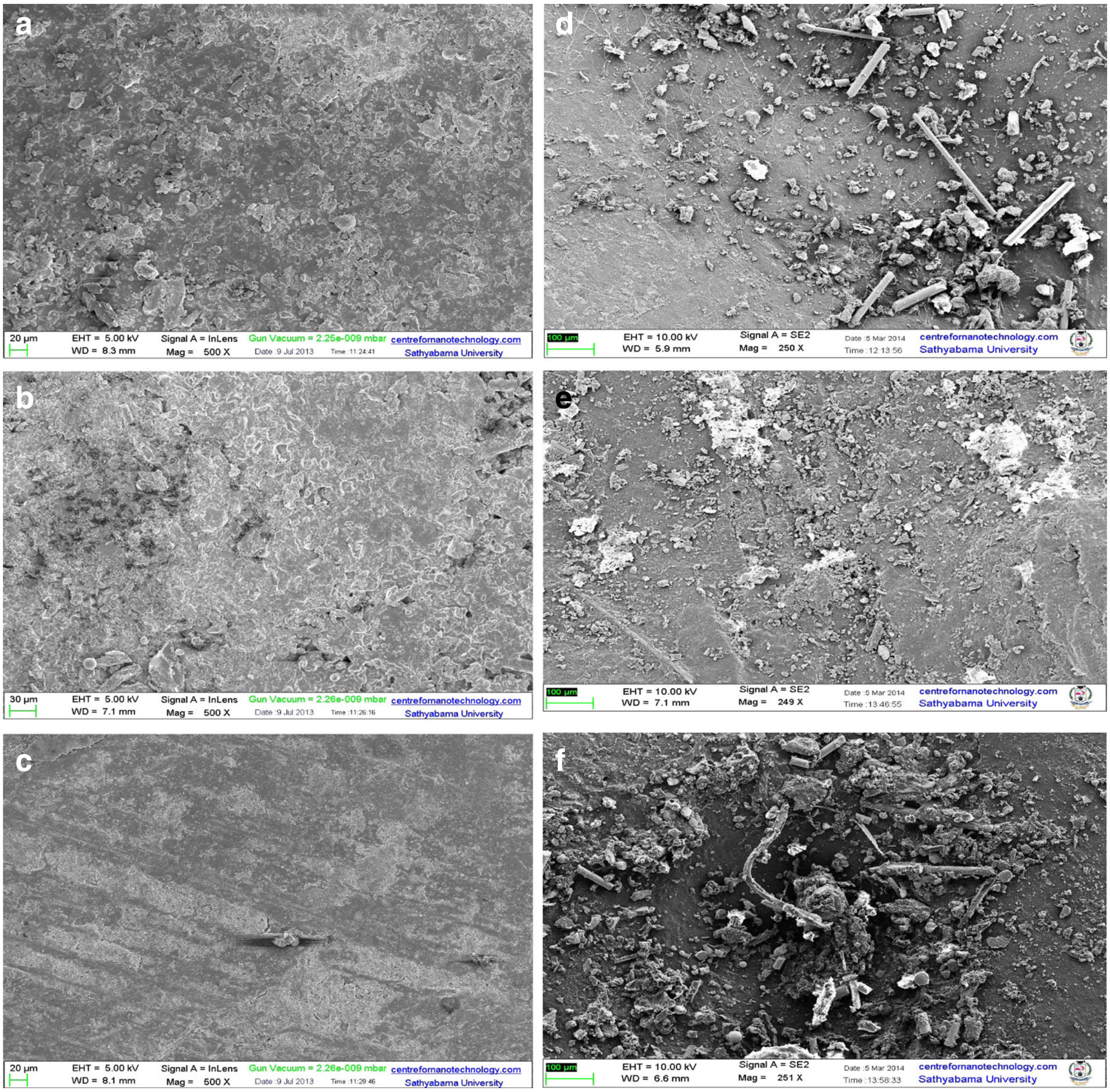

Fig. 19 **a**–**f** Scanning electron micrographs of composite samples with 0, 4 and 6% nanoclay. **a** Images taken from the polished surfaces of 0% nanoclay sample. **b** Images taken from the polished surfaces of 4% nanoclay sample **c** Images taken from the polished surfaces of 6% nanoclay sample **d** Image taken from fracture surface of 0% nanoclay sample. **e** Image taken from fracture surface of 4% nanoclay sample **f** Image taken from fracture surface of 6% nanoclay sample

4 Conclusions

In this paper, the effect of nanoclay and core on low velocity impact and damage tolerance capability of glass/polyester composite laminates has been studied experimentally. Peak load, absorbed energy, displacement at peak load, damage degree and damage area data have been presented and compared with the 0% nanoclay glass fiber reinforced composite laminate sample. The post-impact properties as a measure of damage tolerance of composite laminates have been studied using the flexural after-impact test. The following conclusions have been drawn from the above results:

1. The peak load is found to be highest for sandwich laminate S4 with 4% nanoclay content.
2. Glass fiber reinforced composite laminate G0 absorbed more energy when compared to other laminates for the same impact energy of 30 J.
3. The sandwich laminate S4 showed least displacement at the peak load providing higher stiffness compared to all glass and other sandwich laminates.
4. The damage degree of all the laminates considered in the present study is found to be less than unity. All glass composite laminates G0 showed higher damage degree among all the laminates, indicating poor damage resistance against impact loading.

5. Matrix crack and surface dents are the predominant modes of damage in the glass fiber reinforced laminate sample, while visible damage is found in sandwich laminates.
6. GF laminates have poor damage resistance and tolerance capability which can be enhanced by loading of nanoclay in the polymer and effective sandwich lamination.
7. The sandwich laminate S4 is the most optimum combination of minimum deflection, maximum peak load and better damage tolerance.
8. X-ray diffraction studies of the composite samples have revealed a 51% increase in the gallery spacing of the nanoclay, thus indicating formation of exfoliated nanocomposites.
9. Scanning electron micrographs have also revealed improved adhesion of fibers to the matrix material with nanoclay content.

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