ENERGY ATTENUATION CAPABILITY OF WOVEN NATURAL SILK/EPOXY COMPOSITE PLATES SUBJECTED TO DROP-WEIGHT IMPACTS

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ABSTRACT

The impact energy attenuation and damage characteristics of woven natural silk (WNS)/Epoxy laminated composite panels were evaluated. The Samples prepared in configurations of sandwich WNS/Epoxy/Honeycomb, WNS/Epoxy/Coremat, WNS/Epoxy/Foam and reinforced WNS/Epoxy (reference sample) laminate panels were subjected to low velocity impact loading at energy levels of 32J, 48J and 64J respectively. Impact parameters like load–deflection, load–time and absorbed energy-time behaviour were measured for evaluating the impact performance in terms of load bearing capabilities, energy absorption and failure modes. Evaluation of the results showed that WNS/Epoxy/Coremat displays better load bearing capability qualities compared to the other three samples. In general energy absorption decreases as impact energy increases in all composite samples; WNS/Epoxy/Foam was seen as better energy absorber. Damage areas increased with increasing energy while time to response decreased in all configurations. SEM micrographs show mode of failure as matrix crack, delamination and fibre breakage.

Keywords: woven natural silk, sandwich composites, impact, attenuation of energy.

INTRODUCTION

Sandwich structures which consist of a thick, lightweight core sandwiched between two thin, stiff facings are currently generating interest in the automotive and aviation industries, especially in light weight vehicles (LWV). The core material like foam or honeycomb [1] has characteristically a low density, a small elastic modulus and shear modulus while the facing materials have a high elastic strength and modulus. The primary purpose of sandwich construction is to produce a stiff and strong lightweight structure. This purpose is obviously achieved by attempting to combine the desirable low density property of the core with the high stiffness/strength of the faceplates into one composite structure.

A major concern that limits the usage of composites is their susceptibility to damage due to impact loading; unlike [2] their solid metallic counterparts which are not prone to this susceptibility. Predictions of the effects of impact damage ranging from tool drops, runway debris, bird strikes, hailstorms and ballistic loading, which induce considerable damage to the composite structures and may occur at any time, are still relatively immature.

Early work with graphite/epoxy and Kevlar/epoxy honeycomb sandwiches [3] revealed that significant internal damage is achieved at impact energy levels lower than those required to create visible damage. Oplinger and Slepetz [4] also found a similar behaviour for graphite/epoxy honeycomb sandwich specimens. Since then, many researchers have also confirmed the marked susceptibility of sandwich structures to damage caused by the low-velocity impact of foreign objects [5, 6] by using different test methods and material systems. This type of barely visible external impact damage has been demonstrated to substantially reduce the tensile [3], compressive [7], and bending [8] strengths of the sandwich construction. Lee *et al*., [9] performed an experimental and analytical analysis of a balanced sandwich plate consisting of carbon/epoxy faceplates and polyurethane foam core impacted by a rigid ball. They observed that core transmits both transverse shear and transverse normal (through-thickness) deformations. From their observations, it was noted also that the impacted and non-impacted surfaces of the plate deform differently. More comprehensive and detailed summaries of previous experimental studies can be found in review articles by Abrate [10, 11]. Because of the susceptibility of the composites against impact load the study of low velocity impact on composite structures have been researched extensively. However, it was observed that not much research has been done in the area of woven natural silk laminated composites and no work was reported on woven natural silk reinforced composites and sandwich composite laminates with regard to low velocity impact.

In this study impact tests were carried out on woven natural silk/epoxy reinforced and sandwiched composite plate specimens. Several sandwich materials were used with a view to analysing the absorbing effect of reinforcement and sandwich on impact properties. A low velocity instrumented falling weight impact test method was employed to determine load-deflection, load-time and absorbed energy-time behaviour for evaluating the impact performance in terms of load bearing capabilities, energy absorption and failure modes for phenomenological classification and analytical comparisons.

MATERIALS AND METHODS

The materials involved in this research work includes: (a) Woven natural silk, (b) Honeycomb, (c) Coremat and (d) Foam. Woven natural silk was chosen considering its environmental and mechanical properties

[12, 13, 14] (Table-1). The bombyx mori silk produced by silkworm is among the strongest fibres produced in nature. It is also extremely elastic and resilient. Depending upon how measurements are made, bombyx mori silk is in some cases even better than Kevlar or steel for example, 'elongation at failure' (Table-2). Bombyx mori silk has several properties that are unmatched even by the most exotic of man-made fibres. Bombyx mori silk has a good capacity to absorb energy and to dissipate this energy in a very controlled manner as the silk deforms. This unique property makes this fibre especially attractive for applications where energy absorption is a key design factor.

Table-1. Physical and mechanical properties of unrienforced Epoxy DER 311 and Woven silk fibre.

Properties of DER 311 epoxy		**Properties of woven natural silk fibre**	
Density	1084 kg/m^3	Density	1.4g/cm^3
Compressive strength	131 MPa	Elongation	15%
Tensile strength	63.6 MPa	Modulus of elasticity	22 GNm
Cure time	9-12h	Thickness	0.42 mm
Cure temperature	23.9_C	Ultimate strength	11 GNm

Table-2. Mechanical properties comparison of some natural and synthetic fibres.

Material	**Density** (g/cm^3)	**Tensile strength** (MPa)	**Young's modulus** (GPa)	**Elongation at failure** (%)	**Source**
Bombyx mori silk	1.3-1.8	650-750	16	18-20	(Perez-Rigueiro *et al*. 2000)
Spider silk	1.3	1300-2000	30	28-30	(Craven *et al*. 2000)
Flax	1.5	345-1035	50	2.7-3.2	(Bledzki *et al*. 1999)
Hemp	1.48	690	70	1.6	(Bledzki *et al*. 1999)
Jute	1.3	393-773	26.5	1.5-1.8	(Bledzki *et al*. 1999)
Coir	1.2	175	4.0-6.0	10.0	(Bledzki *et al*. 1999)
Sisal	1.5	155-635	9.2-22.0	2.0-2.5	(Bledzki *et al*. 1999)
Cotton	1.5-1.6	287-597	5.5-12.5	7.0-8.0	(Bledzki *et al*. 1999)
E-glass	2.7	1200	73	2.5	(Bledzki *et al*. 1999)
Carbon	1.8	4000	131	2.8	(Bledzki *et al*. 1999)
Kevlar 49	1.44	3600-4100	131	2.8	(Craven *et al*.2000)

The reference material consisting of woven natural silk and epoxy was made from randomly oriented fibres, with density of 1.4 g/cm^3 and 0.42 mm thick. The final thickness of the WNS/Epoxy composite plate was 3.0mm.

The Kraft paper honeycomb core (Type 60-60-15) was used. For the purpose of this research work 4mm thick of the core and 1.5mm thick of WNS/Epoxy composite laminated skin were used. The core of the other sandwich composite is constituted by a 4mm thick thermoset polyester mat, (commercially known as COREMAT); 1.5mm thick of WNS/Epoxy laminate skin was also applied on both sides of the core. The third sandwich is constituted by 4mm close cell polyurethane foam; with an average cell size of 0.6mm and a nominal density of 52kg/m^3. All core materials were supplied by Dk Composites Snd Bhd (Tables 3, 4 and 5). The final sizes of the composite plates are: WNS/Epoxy = 3mm, WNS/Epoxy/Honeycomb = 7mm, WNS/Epoxy/Coremat = 7mm and WNS/Epoxy/Foam = 7mm

Table-3. Material properties of honeycomb.

Material	**Density** (kg/m^3)	**Compressive strength** (MPa)	**Shear strength** (MPa)	**Cell thickness** (mm)	**Cell size** (mm)
Honeycomb	56	2.02	1.65	0.3175	12.7

Source: Dk Composite Sdn Bhd.

Table-4. Material properties of coremat.

Material	**Density** (kg/m^3)	**Compressive strength** (MPa)	**Compressive modulus** (MPa)	**Tensile strength** (MPa)	**Shear strength** (MPa)	**Shear modulus** (MPa)
Coremat	48	1.1	38	2.0	0.9	29

Source: Dk Composite Snd Bhd.

Table-5. Material properties of foam.

Material	**Density** (kg/m^3)	**Average cell size** (mm)	**Tensile strength** (MPa)	**Compressive strength** (MPa)	**Elongation** (%)
Foam	52	0.6	4.27	3.17	10 -175

Source: Dk Composite Snd Bhd.

Processing method

A hand-layup method shown in Figure-1 was employed to construct the composite samples. The major components required for this method are a vacuum pump, vacuum bagging, spiral tubing, and sealant tape. The spiral tubing ensured a uniform vacuum across the sample and prevented epoxy from pooling on the sample side with less vacuum. This would have occurred on the side without spiral tubing. If epoxy pooling occurs, the facesheet thickness is not uniform. The facesheet would be the thickest on the sample side without the spiral tubing. The core of the sandwich composites consisted of polyurethane foam, a coremat and a honeycomb material. The epoxy consisted of DER 331 resin and Jointmine 905 - 35 hardener, which was allowed to cure under a 600 mm Hg vacuum for a minimum of 9 h. The cured properties of the epoxy, as supplied by DK Composites, are listed in Table-1.

The hand-layup method provided high quality composite plates with minimal defects. To create the sandwich core samples, a layer of epoxy resin was applied before each layer of woven natural silk fabric was placed. Special care was taken to insure the correct amount of epoxy was used in addition to being evenly spread out. After the first four layers were placed foam, honeycomb or coremat were placed. Following this another four layers of woven natural silk fabric were placed to complete the sandwich composite. The vacuum bagging was carefully spread over the sample ensuring no wrinkles would form when the vacuum was applied. Any wrinkles that form on the vacuum bagging will affect the surface finish of the sample. A rubber squeegee was used to remove the extra epoxy and trapped air. A composite produced from WNS and epoxy without core acted as reference.

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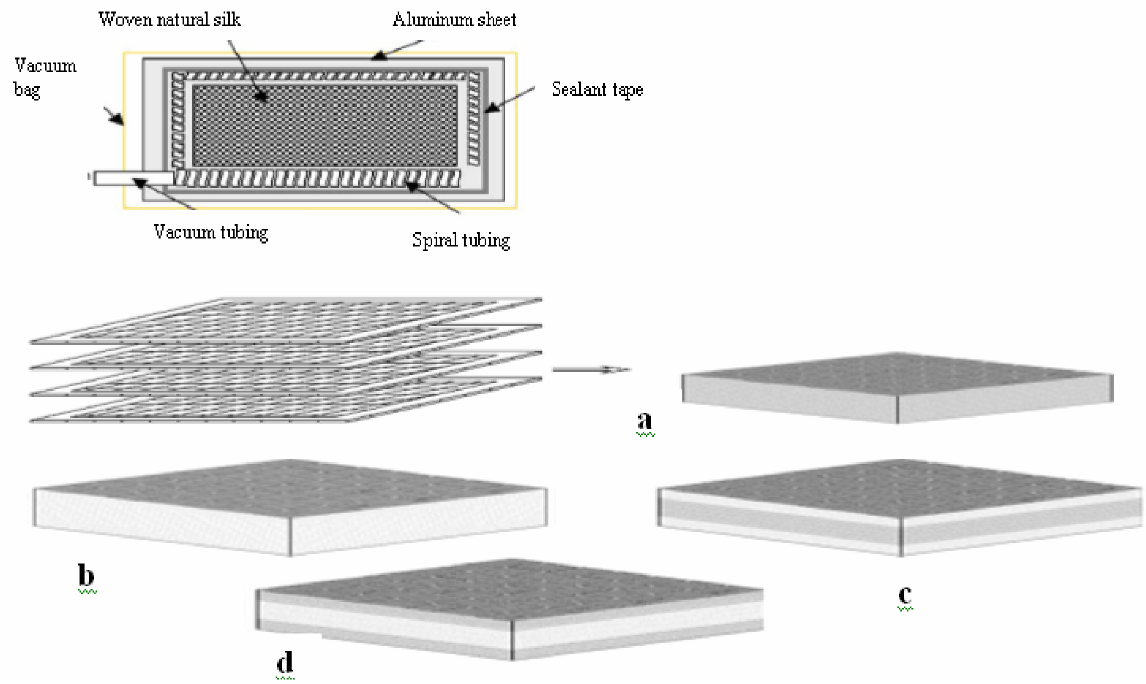

Figure-1. Schematics sample fabrication setup (a) WNS/Epoxy (reference material), (b) WNS/Epoxy/Honeycomb, (c) WNS/Epoxy/Coremat and (d) WNS/Epoxy/Foam. (Each sample Length = 100 and Width =100).

Low velocity impact testing

After the system was set to required conditioning, samples were subjected to low-velocity impact loading using an instrumented impact test setup (Dynatup Model 8250) equipped with an Impulse software data acquisition system (manufactured by GRC Instruments). Samples were clamped at the bottom of the impact testing machine in a sample holder which has a circular support of 75 mm diameter. The weight of the cross-head was maintained at 5.11 kg. Samples were impacted by an instrumented tup with a diameter of 12.7 mm and a hemispherical end. Transient response of the laminates was measured and stored. Impact parameters measured included load, energy, velocity and displacement as functions of time. Dynatup impact testing setup measures the load-time response by the instrumented tup and the impact velocity. The rest of the parameters are calculated using the Laws of Motion [15]. Energy absorbed into the sample is calculated based on the conservation of energy principle which is calculated basis of the initial kinetic energy (KE) of the impactor at the time of impact, instantaneous kinetic energy, potential energy (PE) and the absorbed energy into the sample. For each type of laminates, three samples were impact tested at energy levels of 32, 48 and 64 J. Different energy levels were obtained by varying the drop-height. From the transient response data, load–time response curves were plotted at different energies and superimposed for comparison. Impact parameters like peak load, absorbed energy, time to peak load, deflection at peak load were extracted from the curves and tabulated as listed in Table-3. Impact damage was measured visually from front and back surfaces.

Impact damage assessment

The surfaces of the fractured specimens subjected to impact tests were examined by scanning electron microscope (SEM) JSM 6100 (manufactured JEOL). All the specimens for SEM examination were sputtered with approximately 10 nm thick layer of gold prior to examination in order to avoid charges that may arise.

RESULTS AND DISCUSSIONS

Three specimens were tested in each configuration and the average values of impact test results tabulated.

Effect of configuration on maximum load (kN)

Woven natural silk composite specimens in configurations of sandwich WNS/Epoxy/Honeycomb, WNS/Epoxy/Coremat, WNS/Epoxy/Foam and reinforced WNS/Epoxy were subjected to impact energies of 32J, 48J and 64J respectively. The highest point in Figures 2a-c on the curve designated the maximum load, corresponding to the onset of material damage (radial fracture point) (Figure-5) at this initiation of damage; there is a decrease in material stiffness resulting in a drop in the load time trace. This damage [16] is usually matrix failure, with very little or no visible damage observed upon superficial inspection of the specimen at this point. A second peak is the load corresponding to the onset of circumferential fracture or complete failure. A more damage resistant material will have a higher peak; [17] in other words; the value of maximum load is a function of the damage resistance of a material. Figure-5 shows schematics fracture features of an impacted specimen.

At incident impact energy of 32J, the entire specimen suffered a notable damage WNS/Epoxy/Foam suffered radial fracture (i.e. matrix and woven fibre fracture). The front damage area was about 200mm^2 with a back crack of 20mm length (Figure-6b). WNS/Epoxy/Honeycomb suffered up to penetration (i.e. matrix crack and woven fibre breakage) the depth of tup penetration in the specimen was about 13mm. Front damage area was about 290.93mm^2, back damage area of 176.74mm^2 and a crack length of 30mm (Figure-6a). WNS/Epoxy/Coremat and WNS/Epoxy suffered damages up to perforation (Figure-6c-d). It was observed that the average peak load at which the specimens failed Figure-2a was WNS/Epoxy 0.68kN, WNS/Epoxy/Honeycomb 0.34kN, WNS/Epoxy/Foam 0.92kN and WNS/Epoxy/Coremat 1.35kN (Table-6), respectively.

Table-6. Comparison of impact parameters and damage areas of woven natural silk composite plate samples.

Impact energy (J)	**Sample configurations and average values**			
	WNS/Epoxy	**WNS/Epoxy/Honeycomb**	**WNS/Epoxy/Foam**	**WNS/Epoxy/Coremat**
	Peak load/ kN			
32	0.68	0.34	0.92	1.35
48	0.71	0.30	0.94	0.85
64	0.77	0.28	1.18	1.29
	Absorbed energy /J			
32	8.24	6.85	9.64	8.77
48	5.74	5.72	8.75	8.52
64	5.23	4.49	8.72	8.32
	Deflection at peak load/ mm			
32	6.64	5.47	6.71	6.87
48	6.64	5.64	6.65	6.16
64	6.32	5.61	6.82	6.43
	Time to peak load/ ms			
32	3.11	0.63	2.46	4.19
48	2.06	0.27	1.65	1.97
64	1.47	0.23	1.39	1.82
	Damage area /mm^2 (front)			
32	380.2	380.2	346.4	283.7
48	312.6	314.2	314.2	293.7
64	415.5	706.9	314.2	346.4
	Damage area/ mm^2 (back)			
32	452.4	176.7	78.6	414.5
48	490.9	706.9	490.9	516.4
64	521.7	1256.8	706.9	552.4

WNS/Epoxy/Coremat showed the highest peak load with regard to the reported impact energy. In the case of 48J incident impact energy, the entire specimen suffered damage up to perforation with damage areas increasing as the impact energy increases. Damage area for WNS/epoxy/Honeycomb Figure-7a shown (front) 314.2mm^2, (back) 706.95mm^2 and about 60mm horizontal back fracture other damage areas were as in Table-6. The peak loads Figure-2b showed WNS/Epoxy/Foam displaying the highest record of 0.94kN. Evaluation of sample specimens under incident impact energy of 64J witnessed more damage areas compared to the previous Figure-8a-d supporting the trend that damage areas increasing as the impact energy increases. Mahesh *et al* (2007), [18] Atas and Sayman [19] reported a damage area for WNS/epoxy/honeycomb of 706.95mm2 (front) and 1256.8 mm2 (back) respectively. Generally, observations showed an increase in the peak load (kN) as well as damage areas (mm^2) as the impact energy levels were increased.

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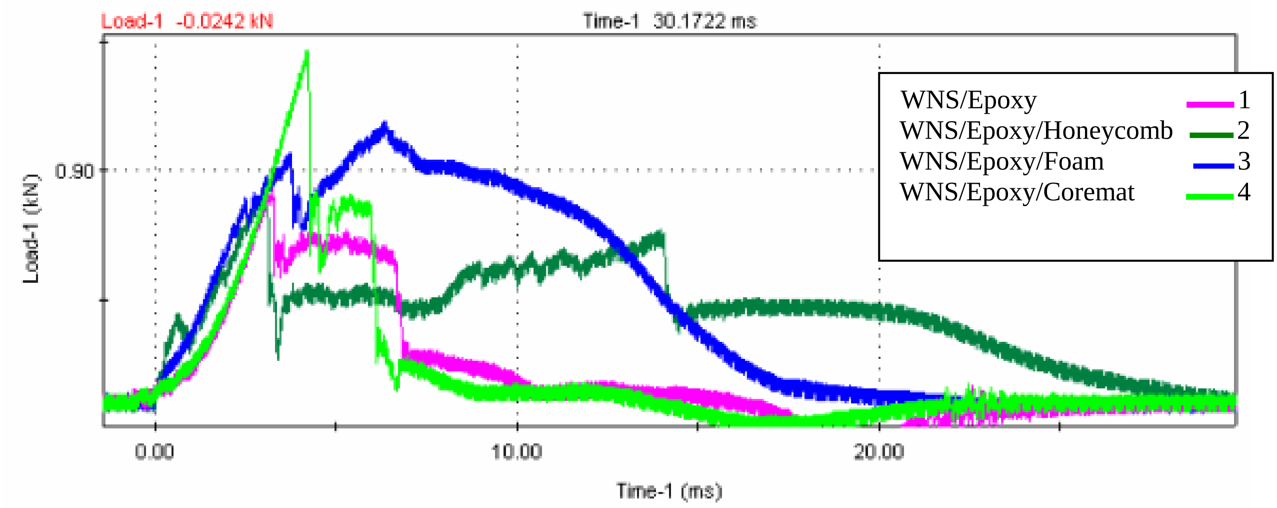

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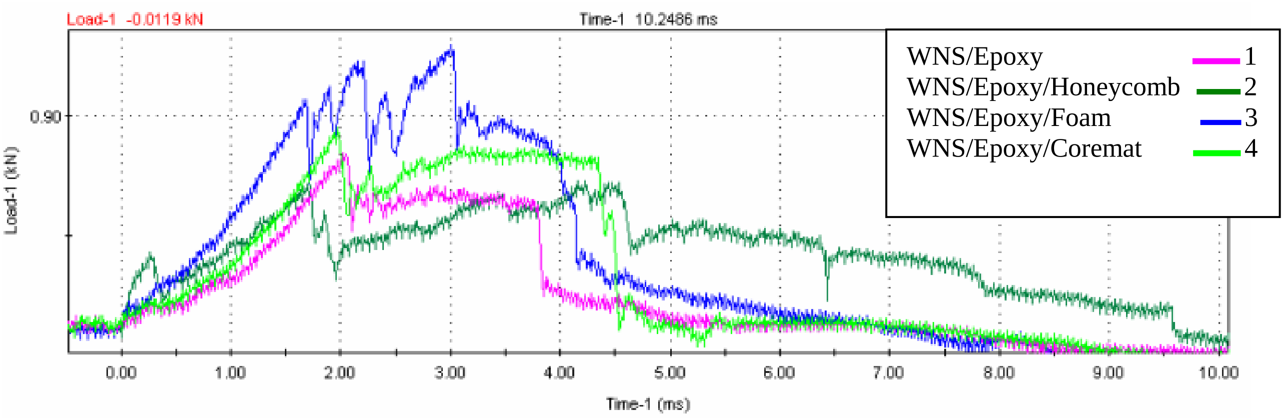

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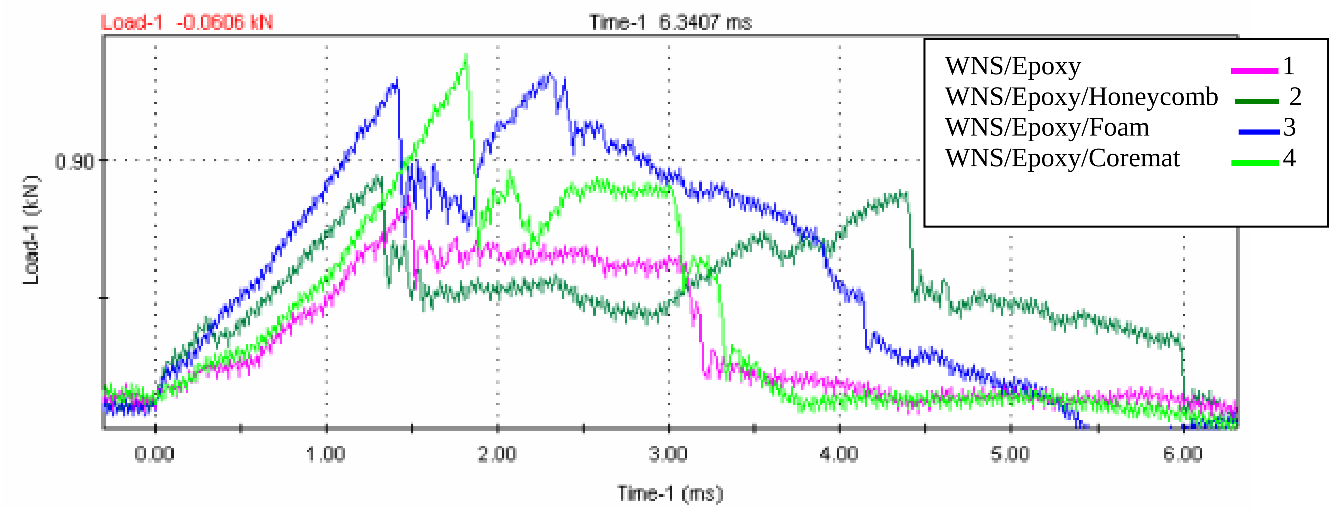

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Figures 2a-c. Curves of impact load versus time of woven natural silk fibre composites panels. (a) Impact load of 32J (b) impact load of 48J and (c) impact load of 68J.

Effect of configuration on absorbed energy (J)

Energy absorbed by the specimen is the energy at the peak load deducted from the total energy. It is assumed that the energy up to the peak load is absorbed through elastic deformation and all the energies that are absorbed beyond that is assumed to be absorbed through the

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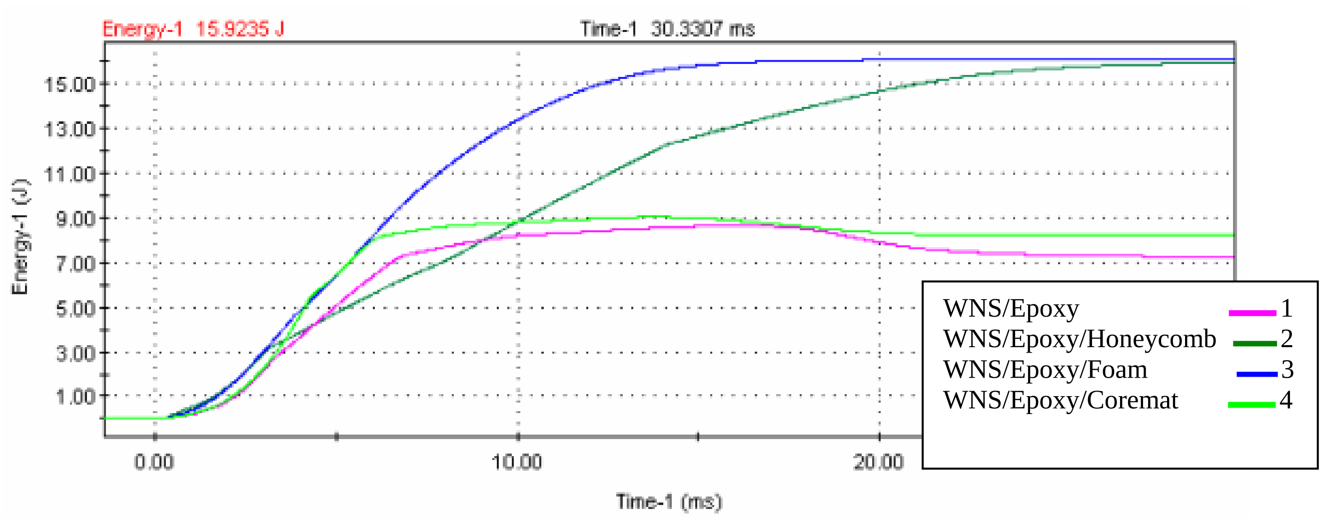
creation of damages. The energy values in Figures 3a-c corresponding to y-coordinate as the on the energy - time plot is the energy at maximum load, which is the energy absorbed by the specimen up to the point of maximum load. The values corresponding to the maxima and their locations were compared for different configuration of natural silk laminated composites plates to ascertain their fracture resistances as well as energy attenuation. The absorbed energies shown in Figures 3a - c at 32, 48 and 64 (J) were observed for WNS/Epoxy/Foam with 9.64, 8.75 and 8.72 (J), for WNS/Epoxy/Honeycomb with 6.85, 5.72 and 4.49J, WNS/Epoxy/Coremat absorbed 8.77, 8.52 and 8.32 (J) and for WNS/Epoxy with 8.24, 5.74 and 5.23 (J) respectively. It was noted in all configurations that the absorption values decreased with increasing impact energy (J). As long as there is no appreciable damage in the sample, the absorbed energy normally increases with the increase in impact energy. Once, there is a dent or penetration in the sample, then the damage tends to become localised and the absorbed energy will consequently be lesser. Not all the energy from the tup will be absorbed by the sample. The energy absorption shown in Figure-3c displayed the highest absorbed energy value of 9.64J for WNS/Epoxy/Foam.



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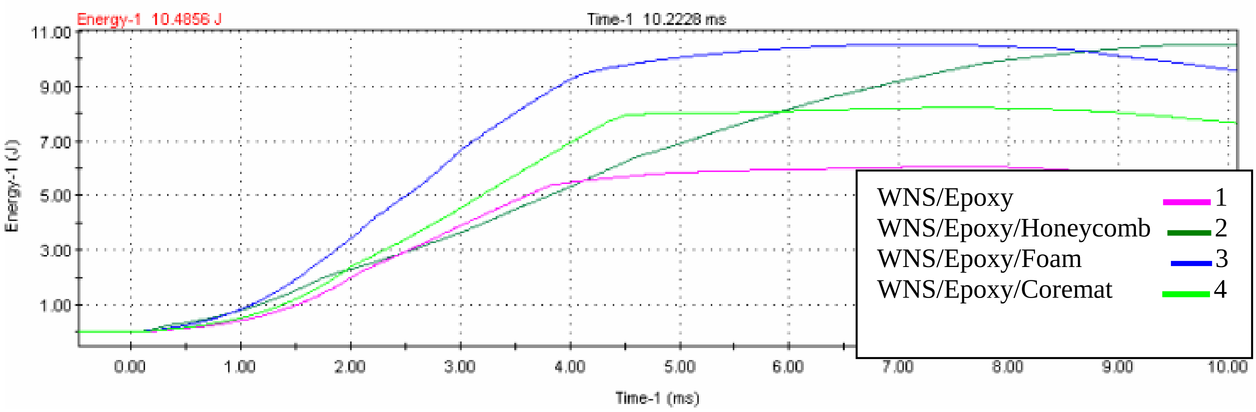

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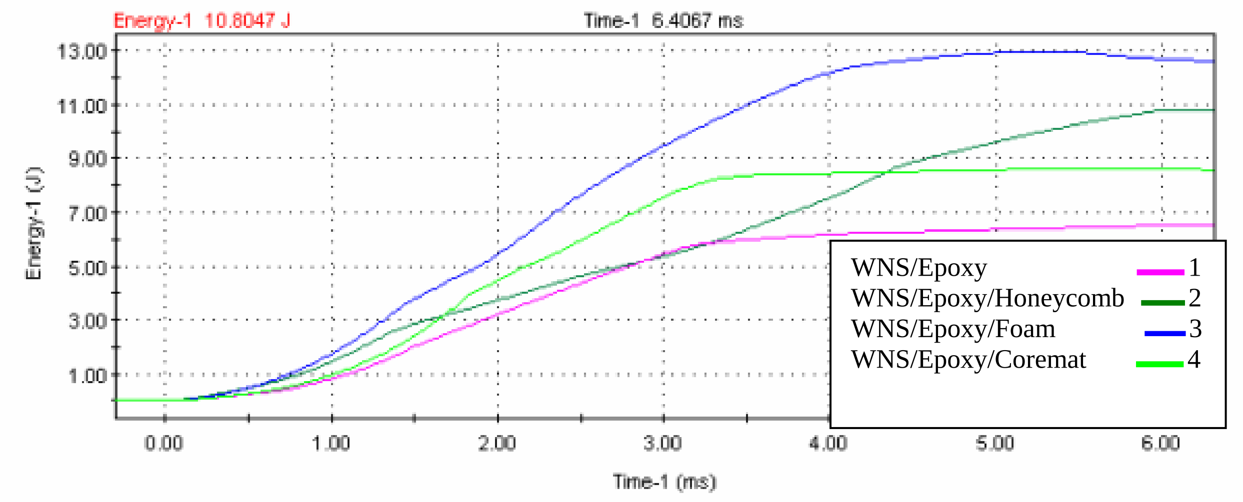

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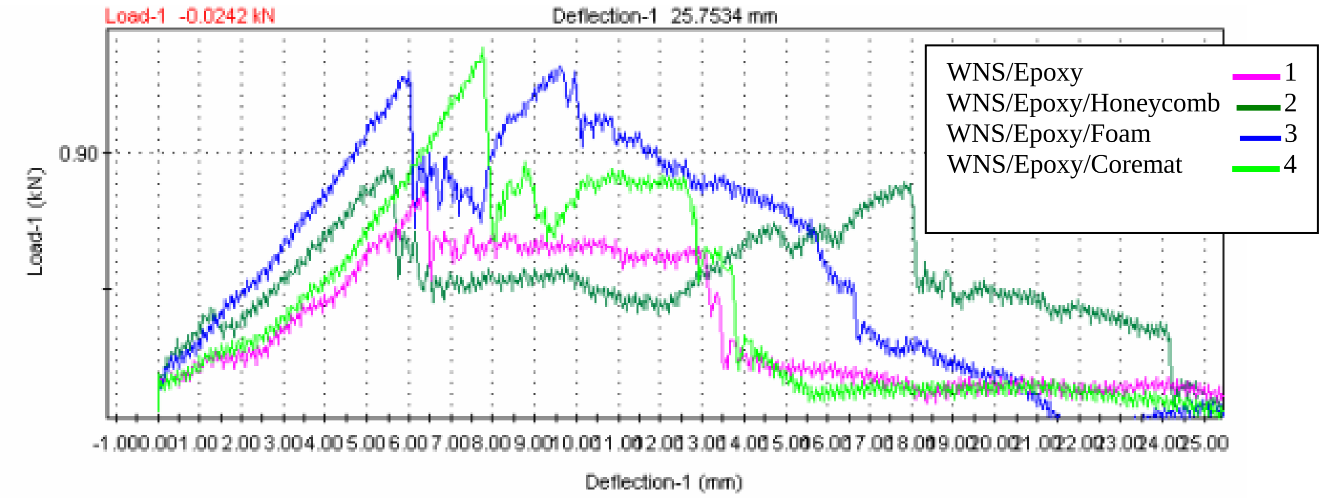
Figures-3a-c. curves of absorbed energy versus time of woven natural silk fibre composites panels. (a) Energy absorbed at 32J (b) Energy absorbed at 48J and (c) Energy absorbed at 64J.

Effect of configuration on deflection

The load-deflection curve in (Figure-4a-c) show a change in stiffness indicating structural degradation on the composite samples. Deflections at peak load for energy levels of 32, 48 and 64 J showed that WNS/Epoxy deflected 6.64, 5.94 and 6.32 mm, WNS/Epoxy/Foam deflected 6.71, 6.65 and 6.82 mm; WNS/Epoxy/Honeycomb deflected 5.47, 5.64, and 5.61 and WNS/Epoxy/Coremat deflected 6.87, 6.16 and 6.43 respectively. The highest deflection value of 6.87mm Figure-4c was registered by WNS/epoxy/Coremat at 32J impacting energy.



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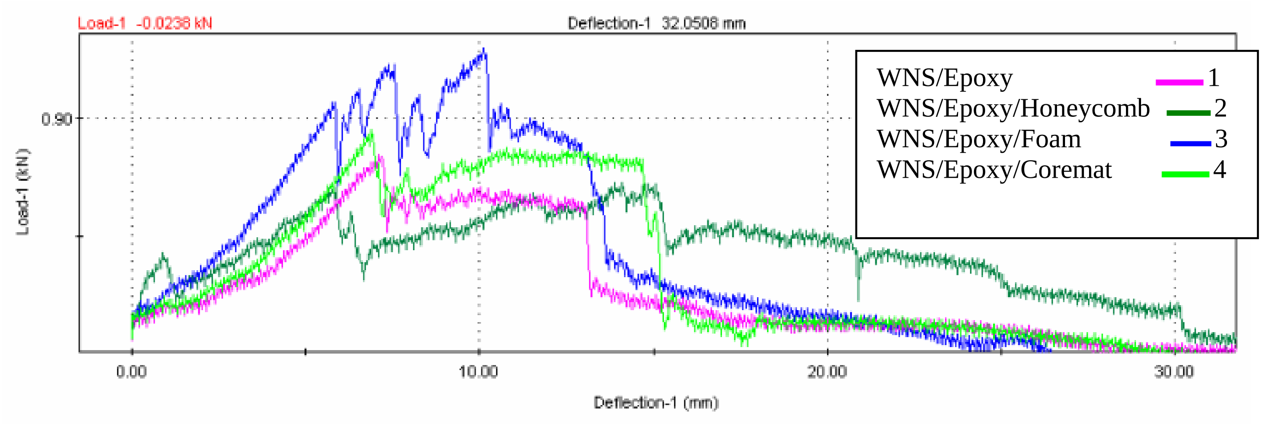

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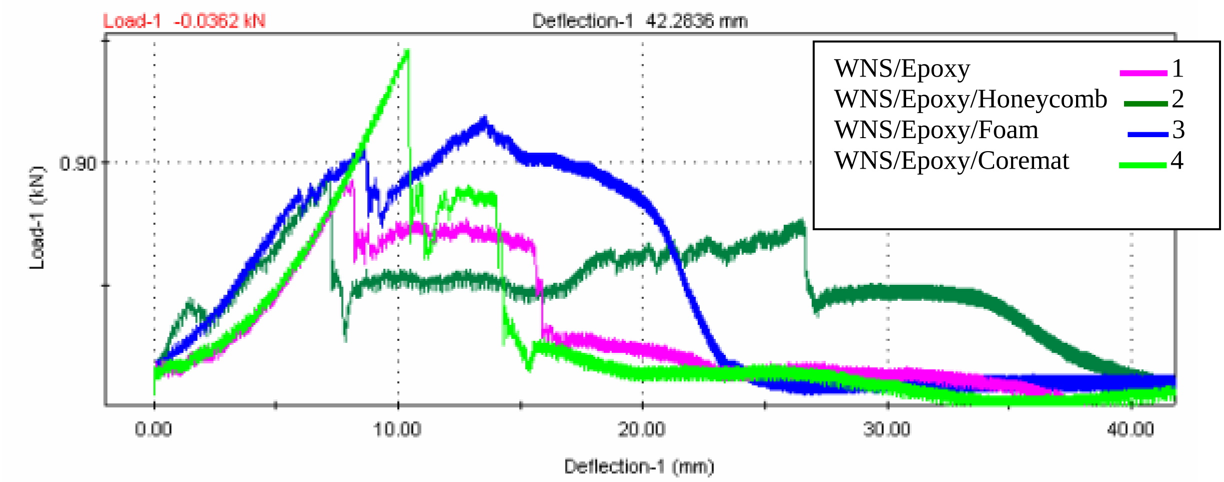

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Figure-4a-c. Performance curves of impact load versus deflection at varied impact loading. (a) Impact loading of 64J (b) Impact loading 48J and (c) Impact loading of 32J.

Effect of configuration on time to maximum load

The x-coordinates of the curves (load/time, energy/time) Figures 2a - c and 3a - c correspond to the time to maximum load of the samples configuration. Time to peak load for 32, 48 and 64J were given as: WNS/Epoxy specimens recorded, 3.11, 2.06 and 1.47minutes, WNS/Epoxy/Foam was 2.46, 1.65 and 1.39 minutes, time to peak load for WNS/Epoxy/Coremat was 4.19, 1.97 and 1.82 minutes and for WNS/Epoxy/Honeycomb was 0.63, 0.27 and 0.23minutes espectively. The highest time to peak load of 4.19 (Figure-2a) at 32J was registered by WNS/Epoxy/Coremat. It was observed that an increase in the incident energy increases the incident velocity hence; the sample will have to react much faster. This result in the lower duration of impact and also the samples reach the peak load much earlier at higher energies. In other words, time decreases with increase in incident energy (J).

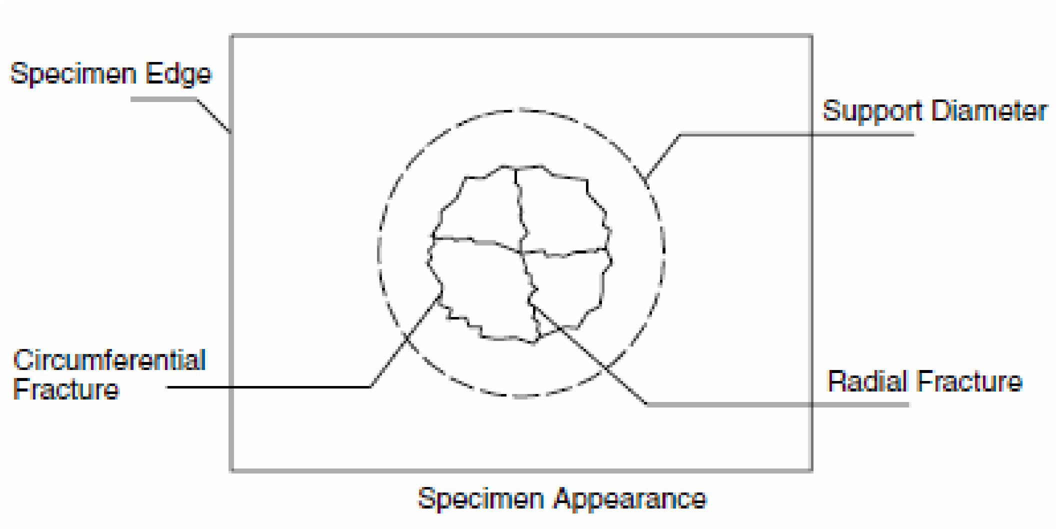
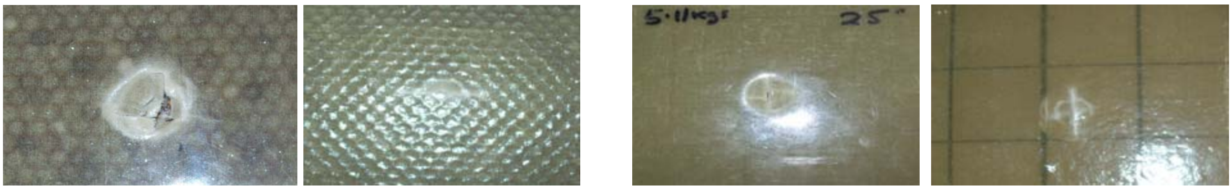
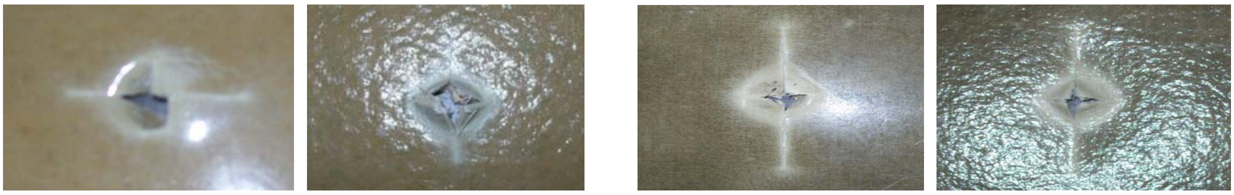


Figure-5. Fracture features of impacted specimens (not to scale).



a front back **b** front back



c front back **d** front back

Figure-6a-d. Samples of specimen subjected to **32J** incident impact energy (a) WNS/Epoxy/Honeycomb (b) WNS/Epoxy/Foam (c) WNS/Epoxy/Coremat (d) WNS/Epoxy.

Effect of configuration on failure mode

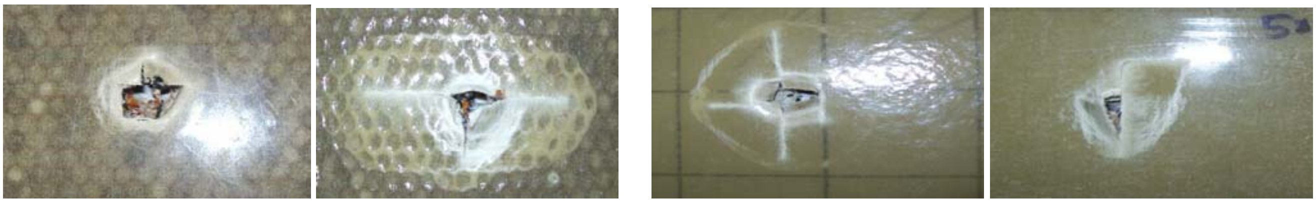
Observations of the damage modes under 32J incident impact energy (J) as displayed in Figures 6a-d showed each configuration with a different extent of damage areas. Figure-6a showed penetration damage on the front side and a strained back side caused by woven natural fabric under tensile stress by the impact energy (fibre breakage, delamination and matrix cracking). Figure-6b showed circumferential and radial fracture damage on the front side, straight and circumferential cracks were observed on the back side (matrix cracking). Figures 6c and d suffered up to perforation, the damage was observed as a combination of matrix crack, delamination, fibre breakage and perforation. Figures 7a-d and 8a-d showed the damage exerted on the specimens at impact energies of 48 and 64J respectively. All samples suffered damage up to perforation; a close observation showed a combination of damage modes as was reported for Figure-6. It was also observed that as the impact energy increases, the laminated composites experienced more damage areas. Sutherland and Soares [20, 21], observed the same type of damage in their work for e-glass/polyester laminates.

One major importance of studying the impact behaviour of composite materials is to characterise the type and extent of the damage induced in the impacted specimens, as several failure mechanisms may appear in the composite materials specimen [22-24].

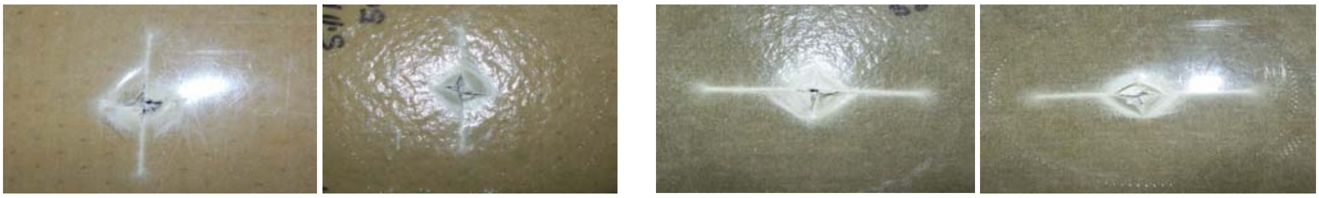
a front back **b** front back

c front back **d** front back

Figures-7a-d. Samples of specimen subjected to **48J** incident impact energy (a) WNS/Epoxy/Honeycomb (b) WNS/Epoxy/Foam (c) WNS/Epoxy/Coremat (d) WNS/Epoxy.



a front back **b** front back



c front back **d** front back

Figure-8a-d. Samples of specimen subjected to **64J** incident impact energy (a) WNS/Epoxy/Honeycomb (b) WNS/Epoxy/Foam (c) WNS/Epoxy/Coremat (d) WNS/Epoxy.

Morphology of failure

Scanning election micrographs of all the specimens impacted by drop force of 64J are shown in Figure-9. It is evident from these specimens that a combination of matrix cracking, delamination and fibre breakage are the predominant failure modes. These failure mechanisms agree very well with the impact damage observed by Errajhi *et al.*, [25] for an aluminized E-glass fibre reinforced unsaturated polyester composites. Similar failure modes have been reported for chopped glass fibre composites [26, 27] for carbon fibre reinforced epoxy composites.

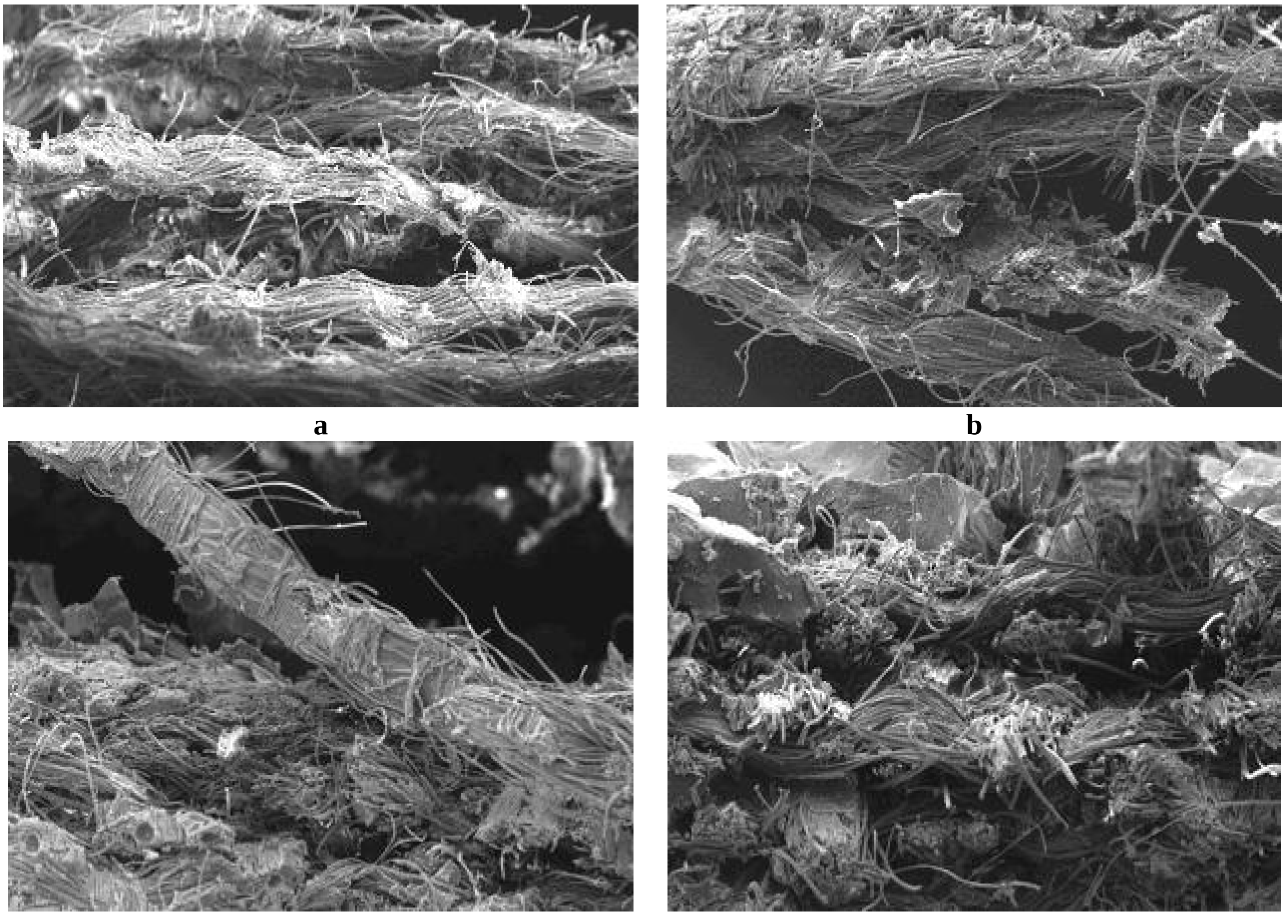


Figure-9. SEM micrographs of fractured surfaces of composites plates @ 250 magnification, showing matrix cracking, delamination and fibre breakage at striking impact energy of 64J. (a) WNS/Epoxy (b) WNS/Epoxy/Coremat (c) WNS/Epoxy/Foam and (d) WNS/Epoxy/Honeycomb.

CONCLUSIONS

A comparison of the load bearing capabilities, energy absorption and failure modes of woven natural silk fabric (WNS) composites in a drop weight impact event were evaluated at 32, 48 and 64J incident impact energy respectively. This study is expected to be helpful in understanding the response of woven natural silk (WNS) fabric composite plates under impact loading**.** The observations made suggest that WNS/Epoxy/Coremat is good for structural applications where load bearing capability is a criterion. For applications where an energy attenuation material is a criterion, WNS/Epoxy/Foam is a suitable choice.

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