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The impact damage response of plain woven natural silk/epoxy laminated composite plates

A. U. Ude*, A. K. Ariffin, K. Sopian, A. Arifin and C. H. Azhari

Department of Mechanical and Material Engineering, Faculty of Engineering & Built Environment,
The National University of Malaysia (UKM), 43600 Bangi, Selangor, MALAYSIA
Corresponding Author: e-mail: albertuche@yahoo.com, Tel: + 6016 2843058

Abstract

This paper presents the impact response of woven natural silk (WNS)/Epoxy composite. The composite specimens were prepared in configurations of 10, 15, 20, 25 and 30 ply of WNS. Drop weight impact test was carried out under varied impact energies of 32J, 48J and 64J. Examinations of load bearing capability, energy absorption capability and damage process from initiation of damage to final perforation, with regards to increasing number of WNS Ply and increasing impact loads were investigated. It was observed that load bearing capability increases with increase in the number of WNS ply. Further investigation of each plate revealed that load bearing capability increases with increase in impact load. The energy absorption capability also increased with increase in the number of WNS ply. It is important to note that as the thickness of the specimen increases, delamination and surface area damage increased. The scanning electronics microscope (SEM) result showed mechanism of failure as a combination of delamination, fibre-matrix debonding, fibre breakage and interlaminar matrix cracking.

Keywords: Impact damage, laminated composites, energy absorption, woven natural silk.

1. Introduction

One of the major concerns in designing composite structures is that composite structures are known to be highly susceptible to internal damage caused by impact loads, even a low-velocity impact. Often times, internal damages are induced on composite structures by light impact while their surface may appear undamaged to visual inspections (Peng and Cao, 2000). The presence of these internal damages in composite structures most often lead to a sudden catastrophic failure. In an attempt to finding solution, woven synthetics materials like Kevlar and Carbon fibres were introduced (Okenwa *et al*., 2002; Cho and Zhao, 2002; Aslan *et al*., 2003). Due to the unfriendly nature of Carbon materials to our environment, the need for alternative eco-friendly materials then arises. This has led to a number of research works on natural fabric composites. Among previous works is Dhakal *et al*. (2007) that investigated the impact properties of non-woven hemp fibre reinforcement subjected to drop weight impact test and their results compared with chopped strand mat E-glass fibre reinforcement with an equal fibre volume fraction equivalent. The impact test results show that the total energy absorbed by 0.21 fibre volume fraction (four layers) of hemp reinforced specimens is comparable to the energy absorbed by the equivalent fibre volume fraction of chopped strand mat E-glass fibre reinforced unsaturated polyester composite specimens. Sapuan and Maleque (2005) worked on the design and fabrication of banana woven fabric reinforcement epoxy composite for household telephone stand. Herrara-Franco *et al*. (1997) illustrated the feasibility of coir (coconut fibre) as reinforcing fibre in different thermosetting and thermoplastics matrices such as phenol–formaldehyde, unsaturated polyester, epoxy, polyethylene and natural rubber. Sapuan *et al*. (2001) carried out investigation on the mechanical properties of coconut fibre reinforced epoxy laminated composites. The fibres were treated with acetylenes, peroxide, stearic acid and potassium permanganate. Flexural and tensile properties were the focus point of their experiment. Andrzej *et al.* (2001) have studied the influence of the type of reinforcing fibre, fibre and microvoid content on the mechanical properties of polyurethane-based composites reinforced with woven flax and jute fabrics prepared with an evenly distributed microvoid foam structure. They reported that woven flax fibre composites have better mechanical strength than the woven jute fibre composites. Khalid *et al.*

(1998) have investigated the experimental and finite element analytical study of cotton fibre reinforced epoxy composites compared with glass fibre reinforced composite. Plant fibres are eco-friendly but their hydrophilic nature is an impediment to their composite structural use (Cicala *et al*., 2009).

This present study introduced Bombyx mori woven natural silk (WNS) as a reinforcement considering its environmental and mechanical Properties. It is among the strongest fibres produced in nature, high specific-strength and high specific-stiffness; extremely elastic and resilient. Previous studies by Bledzki *et al*. (1999), Craven *et al*. (2000), and Perez-Rigueriro *et al.* (2000) showed that Bombyx mori silk is better than Kevlar or steel in terms of elongation at failure. It has a good capacity to absorb energy and to dissipate this energy in a very controlled manner as the silk deforms (Perez-Rigueriro *et al.*, 2000). Because of their structural advantages, improved resistance to impact is expected. The interlacing of fibre bundles in woven fabrics composites prevents the growth of damage and hence provides an increase in impact toughness compared with unidirectional composites. Besides their advantageous mechanical properties, woven fabrics composites are easy to handle and have excellent formability (Dasgupta *et al*., 1992). Therefore, this present investigation seeks to use plain woven natural silk as a new material in low-velocity impact energy attenuations. The study covers the load–time behaviour, load–deflection behaviour, and absorbed energy–time behaviour; velocity – time behaviour and damage fragmentation characteristics for evaluating the impact performance in terms of load bearing capabilities, energy absorption and failure modes. Understanding the behaviour of woven natural silk fabric in an impact event by studying the formation of damages and analysing the absorbing effects under low-velocity impact will lead to improving their damage-resistance characteristics and enhance their employment in air, sea and land transport industries as well as other industries for high-performance applications where light weight and energy absorption are key design factors.

2. Materials and Methods

Three materials were involved in this experiment. The resin used was Epoxy, type (DER 331). A Jointmine hardener, type (905-35) was employed to facilitate curing. Both items were supplied by DkComposites Maleka. The properties of the epoxy as given by the supplies are listed in Table 1. Bombyx mori plain woven natural silk fabric (supplied by Ankasa Indonesia) has been used as the reinforce material. The mechanical properties of which are listed in Table 2 were given by the supplies.

The composite specimens are made by hand- lay–up. This method provided high quality composite samples plates with minimal defects. To create the laminated samples, a layer of epoxy resin was applied before each layer of woven natural silk fabric was placed. Special care was taken to ensure that the correct amount of epoxy was used in addition to being evenly spread out. 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 squeeze was used to remove the extra epoxy and trapped air. The mould was closed and the composite plate was left to cure in a hydraulic press at a room temperature and at a pressure of 10bar for 3hr. After being taken out from the hydraulic press, the plate was left to cure at a room temperature for 24h before being removed from the mould. The plate was then cut into the specimen size for a drop weight impact test using a diamond cutter.

Table 1 Properties of DER 331 epoxy

Density	1084 kg/m^3
Compressive strength	131 MPa
Tensile strength	63.6 MPa
Cure time	9–12h
Cure temperature	23.9 ºC

Table 2 Properties of Bombyx mori plain woven natural silk fabric

Elongation	9%
Modulus of elasticity	22 GNm
Thickness	0.42 mm
Ultimate strength	11 GNm

2. 1 Impact Testing

The tests were performed using an instrumented drop weight testing system, Instron-Dynatup 9250 HV. This system is suitable for a wide variety of applications requiring low to high impact energies. The hemispherical nose tup used was 12.7 mm Diameter. It was assumed to be perfectly rigid. The testing machine has a force transducer with capacity of 22.24 kN. The total mass of the impactor used was 5.5 kg. The composite specimen with dimensions of 100 mm by 100 mm was clamped via a hydro operated clamp on a fixture along a circumference having a 76.2 mm Diameter.

3. Results and Discussions

3.1 Effect of number of ply on maximum load

Figures 1a – 1c show the load versus time curve under 32J, 48J and 64J impact load.

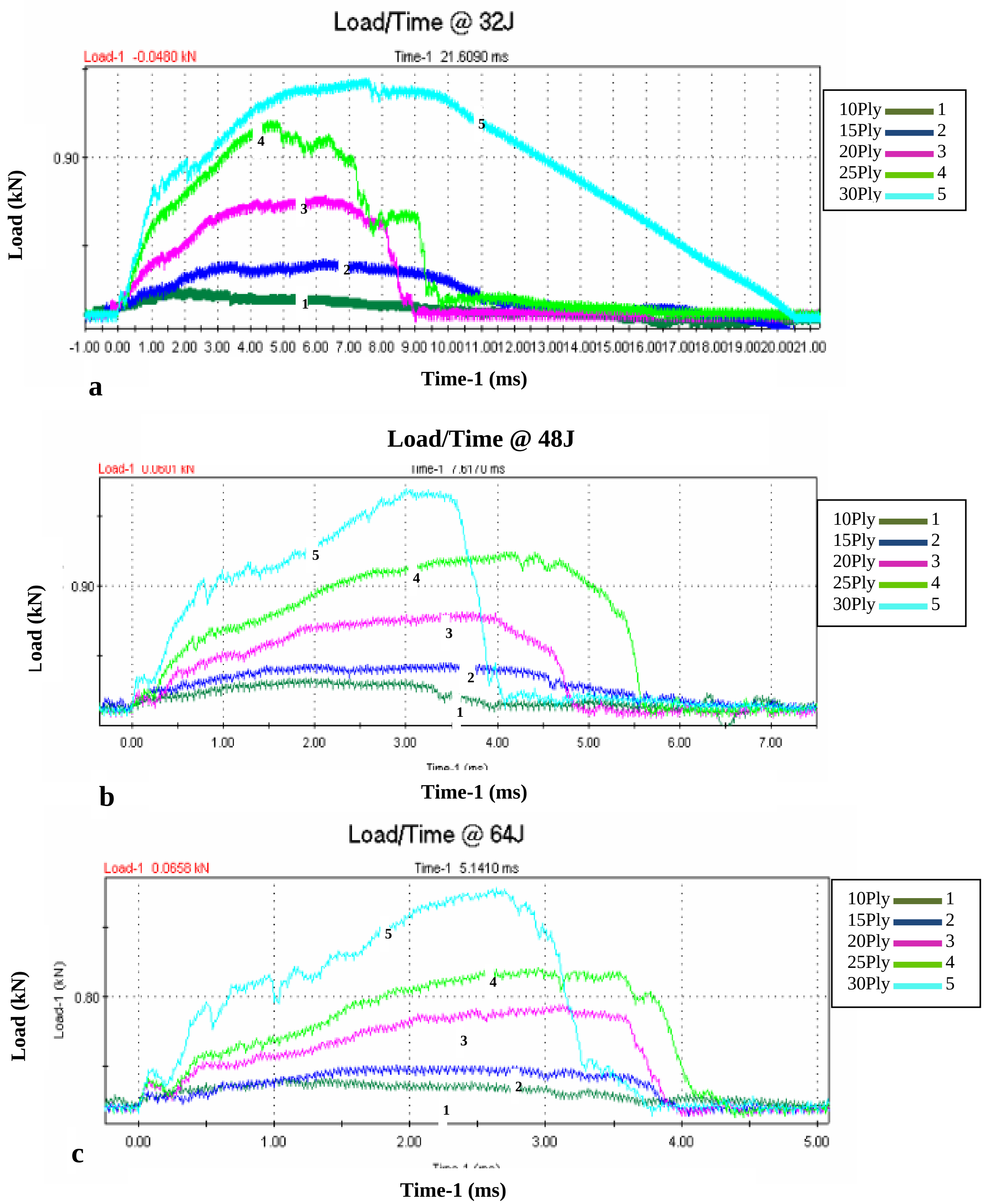


Figure 1. Curves of impact load versus time of woven natural silk fabric composite plates. (a) Impact load of 32J (b) Impact load of 48J (c) Impact load of 64J

Generally, it was obvious that load bearing capability increases as the volume of reinforcement increases, though the geometry of increase could not be quantified. The difference between each specimen was an additional 5ply of WNS but the rational of increase were not evenly distributed as thought. Observations of Figure 1a showed a clear peak increase between each configuration of plies. The 30ply specimen showed a larger curve profile. In Figures 1b and 1c it was noticed that configurations 10 and 15 plies showed a slim increase while others showed significant peak increase. The 25ply specimen showed a larger curve profile in both categories.

The value of maximum load is a function of the damage resistance of a material, in other words, a more resistant material will have a higher value of maximum load/peak (Razi and Raman, 2000). The highest point on the maximum load curve corresponding to the radial fracture damage point. This point marks the onset of failure in the material as this initiation of damage induces a decrease in material stiffness, resulting in a drop in the load time trace. This damage is usually matrix failure, with very little or no visible damage observed upon superficial inspection of the specimen (Siow *et al.*, 1998). A second peak is the load corresponding to circumferential fracture or complete failure. A larger curve profile shows the ability to withstand for longer period of time. It was generally observed as expected, that peak load increases with increase in the number of woven natural silk fabric ply. Since the rational of increases in all the specimens could not be clearly quantified due to inconsistency, defects associated with composite laminate could be a factor. Comparisons of the three categories of impact load (32J, 48J and 64J) showed that peak loads decreases with increase in impact energy.

3.2 The Effect of Increased Load on Load Bearing Capability of the Composite plates

The effect of increased loads on each composite configuration was examined, the results show that values of peak loads increase with increase in impact load. In Figure 2, 30ply configuration showed an increase of 1.35, 1.6 and 1.72 (kN) under impact load of 32J, 48J and 64J respectively. Other configurations also maintained increased values. This increase proved the resistance capability of WNS/Epoxy composite to increasing impact loads.

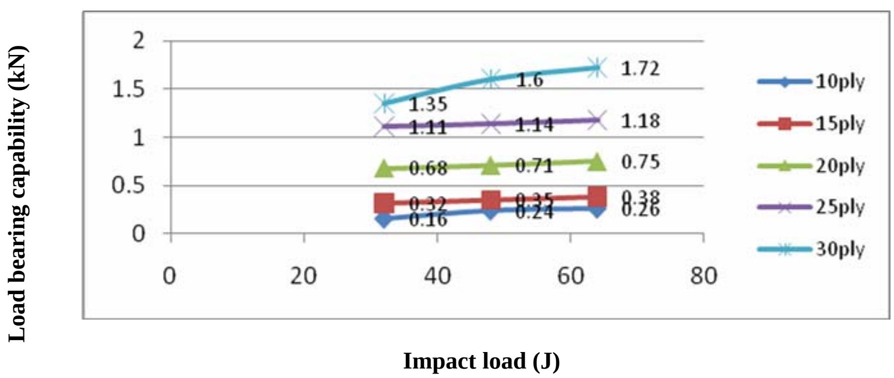


Figure 2. The effect of increasing load on the composite plates

3.3. Effect of Number of Ply on Deflection

The load–deformation behaviour for impacted specimens under 32J, 48J and 64J are shown in Figures 3a – 3c. Change in stiffness for 10 and 15 ply configurations in Figure 3a were observed at 0.1kN corresponding to 2mm deformation. For 20ply specimen the change in stiffness was indicated at approximately 0.4kN corresponding to 4mm deformation. In the case of 25 and 30 ply specimen degradation began at approximately 0.6kN corresponding to 4mm and 0.7kN corresponding to3mm respectively.

A change in stiffness indicates the onset of structural degradation on the composite. The 30ply configuration showed a higher value of peak loads at initiation of failure than for other specimens. This tends to prove that increasing the number of ply increases the stiffness of the composite. In Figures 3b and 3c under 48J and 64J impact energy, the trends were approximately the same. Comparison of the three categories showed load bearing capability increasing while deformation decreases. 30ply specimen increased to 0.9kN and approximately 0.8kN; but showed decrease in deformation at 2.5mm and 2mm respectively.

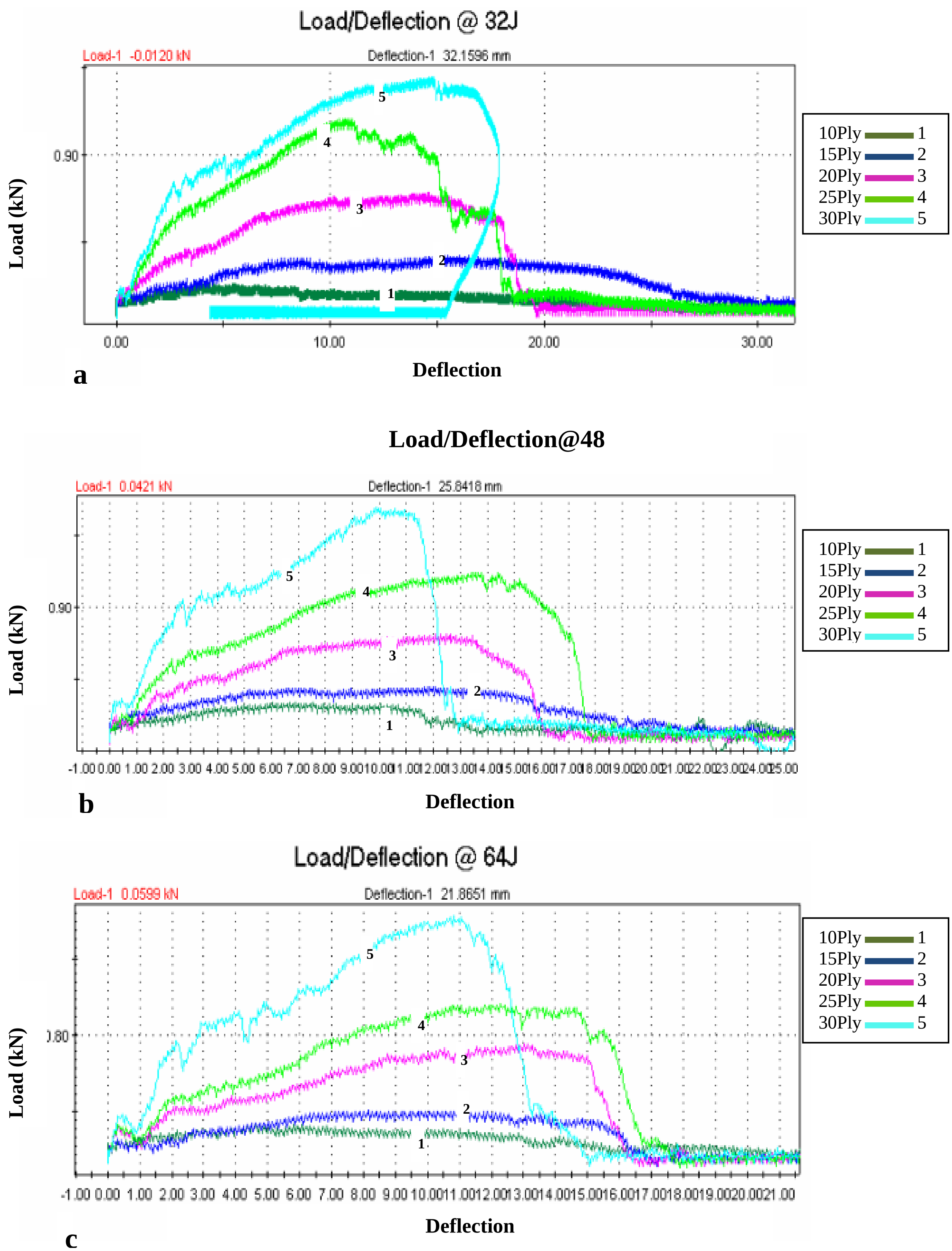


Figure 3 Load – deflection curves under (a) 32J (b) 48J (c) 64J impact energy.

3.4. Effect of Number of Ply on Absorbed Energy

In Figure 4a the specimens were impacted under 32J impact load. Total absorbed energy was recorded as followed: 10ply:1.96J, 15ply: 6.17J, 20ply: 9.26J, 25ply: 13.8J and 30ply: 16.84J respectively.

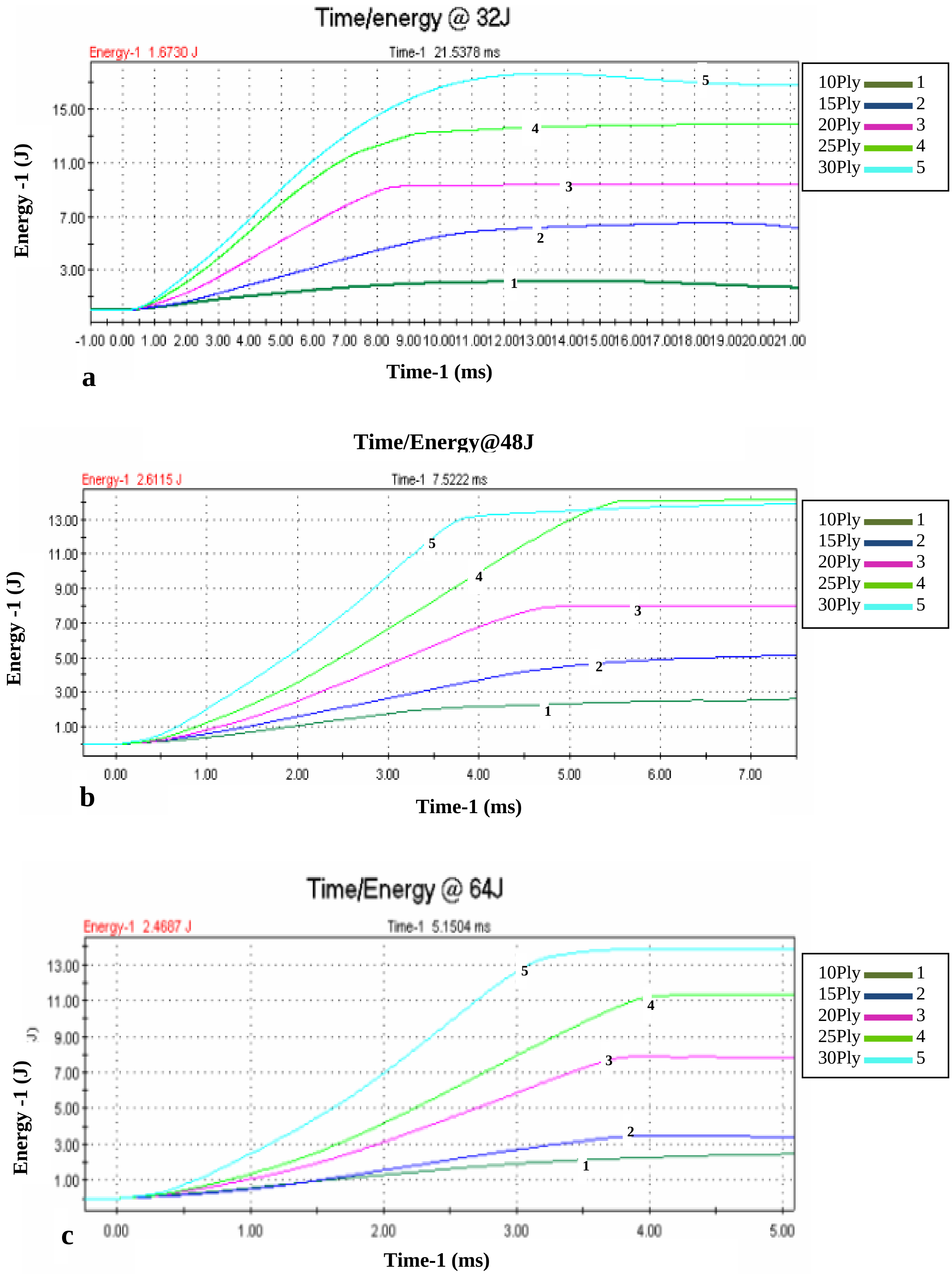


Figure 4. Energy absorption versus time curves under: (a) 32J (b) 48J and (C) 64J

The results of absorption of energy showed that more energy was absorbed with increase in the number of woven natural silk ply. Similar results were also obtained for specimens under 48J and 64J impact load in Figures 4b and 4c. The absorb energy values under 48J impact load were as followed: 10ply: 2.15, 15ply:5.1, 20ply:7.9, 25ply:14.1, 30ply:13.8. The absorb energy under 64J impact load were as followed: 10ply: 2.44, 15ply:3.46, 20ply:7.9, 25ply:11.4, 30ply: 13.9 respectively.

Absorbed energy is the energy absorbed by the material at the peak load deducted from the total energy. The energy absorbed by the materials up to its peak load is assumed to be absorbed through elastic deformation. All other energies that are absorbed beyond this point are assumed to be done through the creation of damages in the material specimen. The energy values in Figures 4a – 4c corresponding to y-coordinate on the energy – time curve is the energy value at maximum load. This value marks the energy absorbed by the material up to the point of maximum load (Dhakal *et al.*, 2007). These 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, with respect to variations in the number of ply. The comparison proved that energy absorption increases with increase in number of WNS ply. It was noted that the absorbed value of 25ply Figure 4b exceeded that of 30ply, this may be attributed to samples defects as it was not anticipated and other specimens also proved otherwise.

3.5 The Effect of Increased Load on Energy Absorption of the Composite Plates

The effects of increasing load on the absorption capability of each ply configuration were shown in Figure 5. Investigations showed different type of curve associated to each configuration of ply. The absorption of energy does not increase with increase in impact load as it was the case with increase in number of ply. Rather, every configuration displayed increase and decrease at different stages of applied impact load. The values suggest that absorption capability of a specimen as the load increases could be affected by the internal structures of the specimen. These includes homogenous distributions of fibre and the matrix, the interface bounding between the fibre and matrix, voids created by trapped air and laminations caused by unlapped woven fabrics.

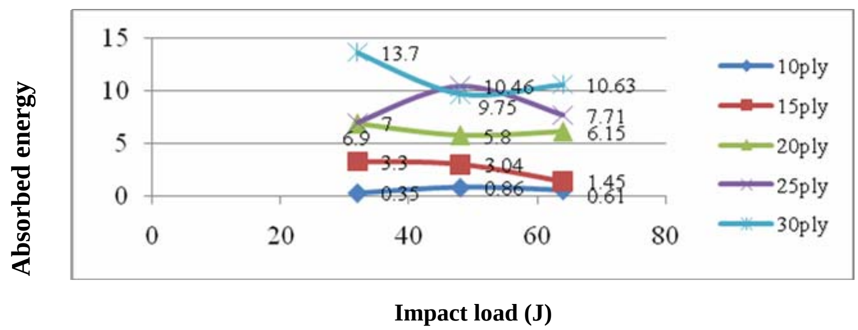


Figure 5. The absorption capability comparison of each composite category with increasing load

3.6 Effect of impactor Velocity on Composite Plates

Figures 6a – 6c, compares the velocity–time curves for different ply specimen. The striking velocity of specimens under 32J was 2.6199 m/s Figure 6a. It was observed that 10ply configuration did not cause a notable velocity loss to impator. The residual and the striking velocity were approximately the same. The 15ply specimen caused a velocity loss of approx. 0.35m/s to the impactor. The 20ply and 25ply specimen showed approx. 0.7m/s and 1.4m/s reduction to the velocity. The 30ply specimen exhibited the highest loss of velocity as it was observed to have reduced the striking velocity to approx. Zero. (Damage samples of this specimen showed that there was no penetration). The incident velocity under 48J and 64J increased to 3.4497m/s and 4.2441m/s Figure 6b and 6c respectively. It was observed that the trend of lost of velocity by the specimens remained similar.

Although impact velocity alone does not describe the impact properties of a material but it can affect the energy dissipated during an impact (Bartus *et al.* 2004). The change of the impactor's momentum as it passes through the specimen relates to the energy consumed by the fracture process. The velocity of the impactor becomes zero when the composite specimen reaches its maximum deflection. In comparison, the trend confirms that the higher the number of WNS ply, the greater the residual velocity. The damage formation of the specimens in Figure 7 show that as the velocity increases the specimens incurred more damages.

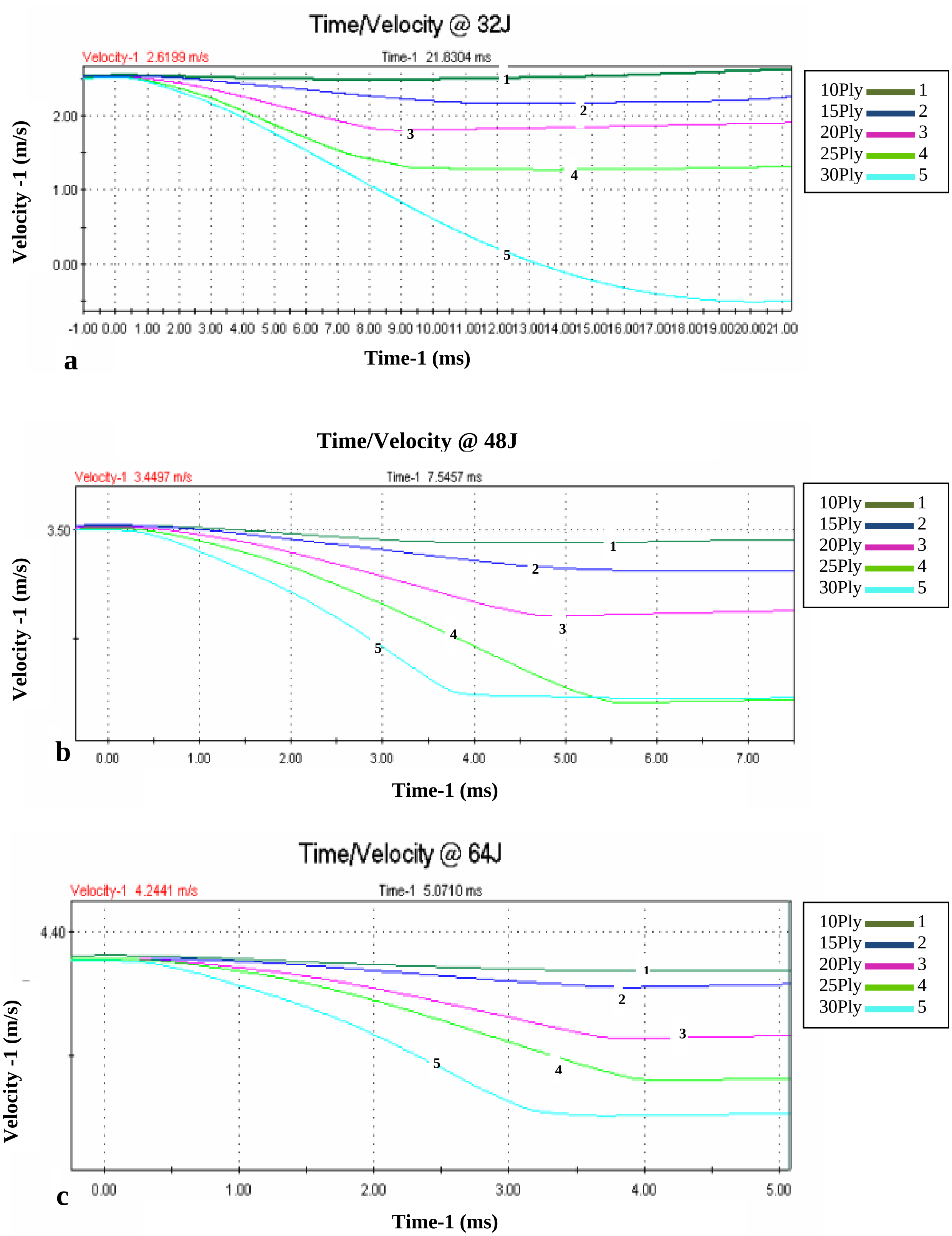


Figure 6. Velocity – time curve for different ply at impact energy level (a) 32J (b) 48J (c) 64J

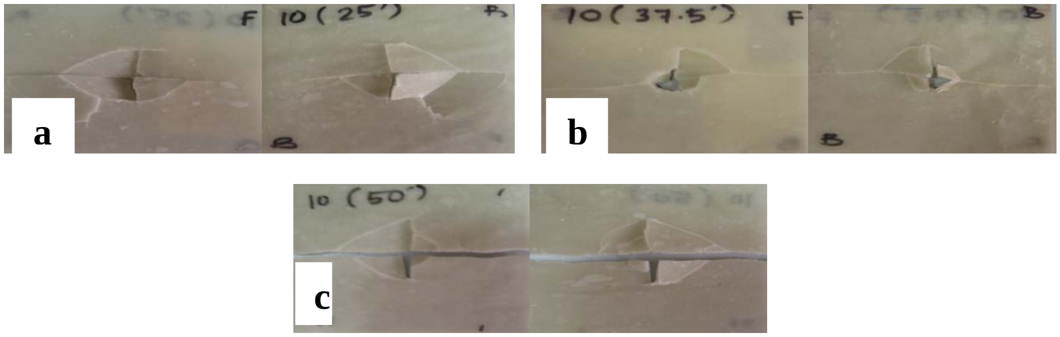


Figure 7. Damage formation on 10ply WNS/Epoxy under varied velocity (a) 32J (b) 48J (c) 64J

3.7 Effect of Number of Ply on Fragmentation Characteristics

Matrix deformation and micro-cracking, interfacial debonding, lamina splitting, delamination, fibre breakage and fibre pull-out are the possible modes of failure in composites subjected to impact loading. Even though fibre breakage is the ultimate failure mode, the damage would initiate in the form of matrix cracking or lamina splitting and would lead to delamination. The damage progression of each configuration of ply were investigated under 32J, 48J and 64J impact load.

3.8 Characteristics of Composite Plates under 32J Impact Load

Under 32J impact loading, except for 30ply all other configurations suffered damages up to perforation. Circumferential and radial damages were predominant. Figure 8a shows that its circumferential front damage area was 157mm^2, back damage area was 157.0mm^2 and 80mm horizontal crack. Figure 8b shows front damage area of 141.4mm^2, back damage area of 141.4mm^2 and horizontal 78mm. Figure 8c show front damage area of 125mm^2, back radial damage of 125mm^2 perforation hole and 10mm crack on one side, In Figure 8d front damage area was 94.2mm^2, back radial and perforation damages. Figure 8e only showed front damage as 50mm horizontal crack and 30mm vertical crack. While the damage sustained at the back was 70mm and 30mm crack length.

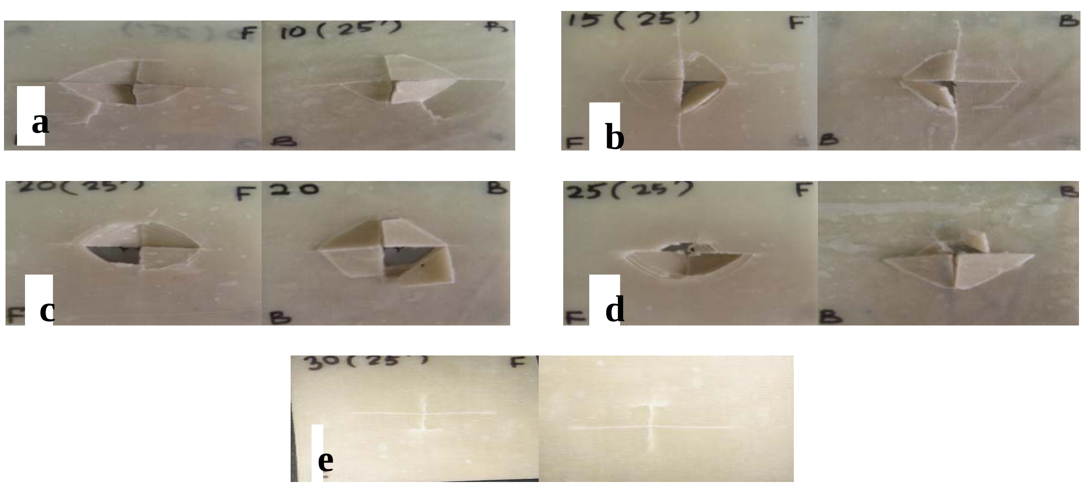


Figure 8. Specimens under 32J impact loading. (a) 10ply (b) 15ply (c) 20ply (d) 25ply (e) 30ply

3.9 Fragmentation Characteristics of Composite Plates under 48J Impact Load

The entire specimen suffered damage up to perforation indicating that damage areas increasing as the impact energy increases. The paten of damage in the entire configuration was similar with radial and circumferential damage being dominant. The difference was in the size of damage areas incurred by each configuration, as the size of ply increases. Figure 9a showed perforation hole of 10mm, circumferential damage area of 94.2mm^2 and 98mm crack damage. The back surface suffered radial and circumferential damage. Figure 9b showed 5mm perforated hole with front damage area of 113.6mm^2 and 95mm crack. The back of this specimen also suffered a combination of radial and circumferential damages. Figure 9c showed front damage area of 102.1mm^2, 7mm perforation hole. The back of this specimen was prism shape damage. Figure 9d showed front damage areas of 125.6mm^2. Figure 9e showed front damage areas of 106.8mm^2. It was observed that the back damages of Figures 9c, 9d and 9e were similar in shape, the thickness of these specimens is believed as the cause.

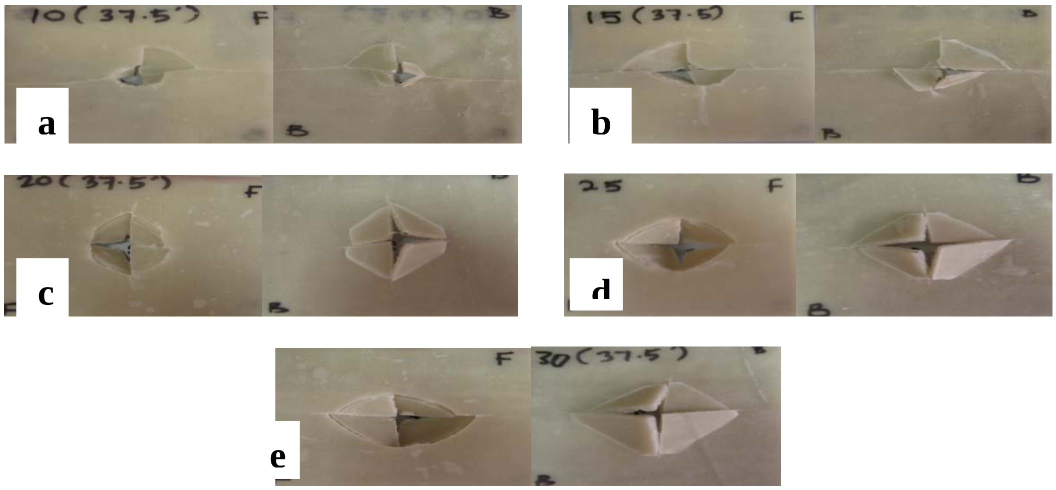


Figure 9. Specimens under 48J impact loading. (a) 10ply (b) 15ply (c) 20ply (d) 25ply (e) 30ply

3.10 Fragmentation Characteristics of Composite Plates under 64J Impact Load

The specimens under 64J impact load suffered more damages than the others. Figure 10a show specimen splitting apart and front damage area of about 141.4mm^2. Figure 10b showed front damage area of 94.5mm^2, crack of 90mm and 20mm perforation hole. Figure 10c showed perforation hole and area damage of 90mm^2. The back of this specimen had one side of the prism shape damage open. Figures 10d and 10e showed front damage areas of 80mm^2 and 70.6mm^2 respectively, the back damages of these specimens showed a prism shape.

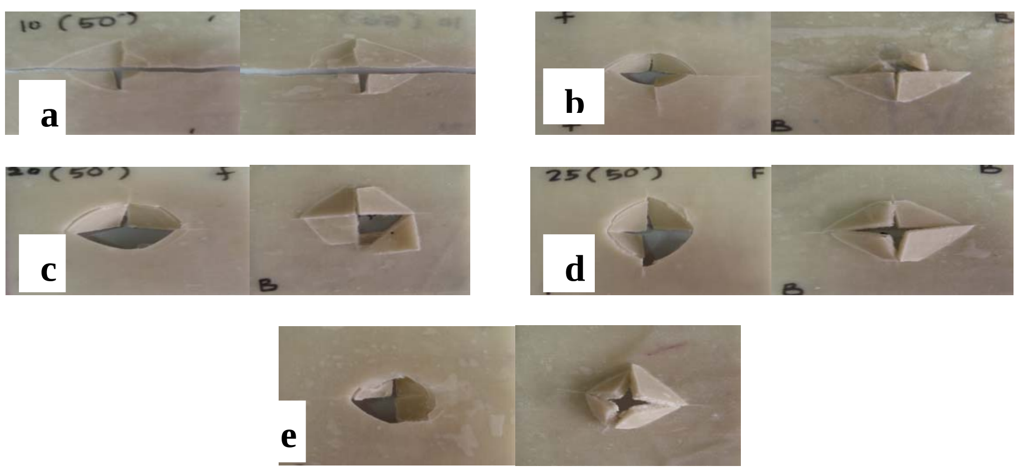


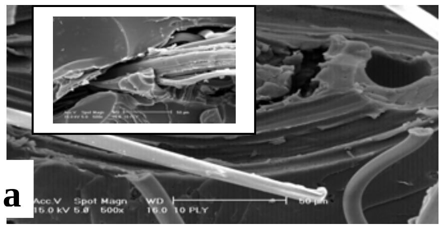
Figure 10. Specimens under 64J impact loading. (a) 10ply (b) 15ply (c) 20ply (d) 25ply (e) 30ply

3.11 Failure Mechanisms

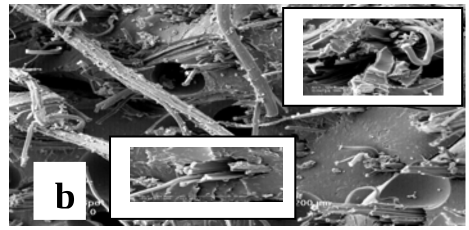
An impact on composite laminates can cause various types of damages including matrix cracking; delamination; fibre breakage; penetration and perforation of the impacted surface. The important step in studying the impact behaviour of composite materials is to characterise the type and extension of the damage induced in the impacted specimens. Several failure mechanisms other than the once named above may appear in the composite materials. SEM photographs of all the impacted specimens under 64J impact load are shown in Figure 11. This set was chosen because they all incurred notable damages up to perforation. There is strong evidence from these specimens in Figures 11a – 11e that a combination of matrix cracking, delamination and fibre breakage are the predominant failure modes. These failure mechanisms agree very well with the impact damages reported by (Corum *et al.* 2003; Rio *et al.* 2005) for chopped glass fibre composites and Carbon fibre reinforced Epoxy matrix composites.

Further investigations of the specimen photographs in Figures 11a – 11e, prove that their modes of failures are similar irrespective of the number of ply. They all involved a combination of failures. In Figure 11a and 11b, showed matrix cracking, matrix splattering, delaminations, fibre pull-out and fibre breakage. In Figure 11c and 11d, there were voids, fibre pull-out, matrix cracking and fibre breakage. In Figure 11e, a combination of matrix cracks, delaminations, fibre breakage and fibre pull -out were seen. This behaviour seems to be one of the advantages of using woven fabrics other than unwoven. It was reported by Ude *et al.* (2007) that low volume of fibre creates vacant spaces, and there is not enough fibres to restrain matrix; causing resin rich areas present which can lead to highly localised strain. Authors like Rong *et al*. (2001), Mohanty *et al.* (2006), Yoldas (2009) and

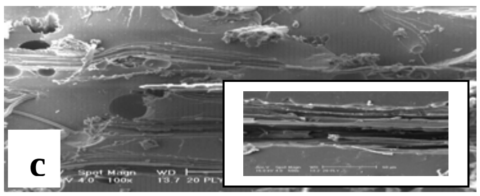
Mohamed *et al.* (2010) also reported that as the fibre weight fraction increase, the wettability of fibre with resin decreases and weak interfacial bonding potentially occurs. This is not the case in woven natural silk laminates as proved by these micrographs.



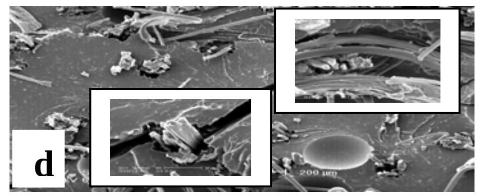
10ply of woven natural silk fabrics



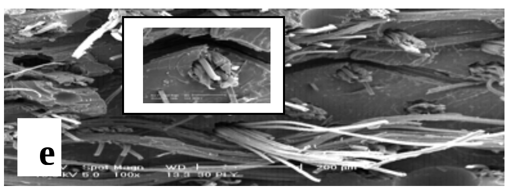
15ply of woven natural silk fabrics



20ply of woven natural silk fabrics



25ply of woven natural silk fabrics



30ply of woven natural silk fabrics

Figure 11. SEM of the specimens under (a) 10ply (b) 15ply (c) 20ply (d) 25ply (e) 30ply

4. Conclusions

An investigation has been conducted to study the impact response of plain woven natural silk (WNS)/Epoxy composite. Parameters used for the study were peak load capability, deflection resistance, absorption capability, velocity loss; failure mechanism and fragmentation characteristics. The findings of this research include:

- There is an increase in energy absorption and peak load as the number of WNS ply increases.
- With an increase in the impact energy, there is an increase in peak loads.
- The composite material incurred more damages with an increase in striking velocity of the impactor.
- The SEM revealed the combination of matrix cracking, delamination, fibre debounding, fibre pull-out and fibre breakage as the failure mechanism irrespective of the number of ply.
- The WNS/Epoxy composite plate could be applied for structural usage in the fabrication of light weight bodies and other composite structures where energy absorption is a key design factor.

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Biographical notes

A. U. Ude is a PhD student and research assistant in the Department of Mechanical and Materials Engineering, National University of Malaysia (UKM). He obtained HND in Mechanical Engineering from Institute of Management and Technology (IMT), Enugu, Nigeria, in 1998 and M.Eng in Mechanical Engineering from The National University of Malaysia (UKM) in 2006. His research interests are composite materials, mechanical design, impact simulation and polymer processing.

A. K. Ariffin is a Professor at the Department of Mechanical and Materials Engineering, UKM. He graduated with a Bachelor in Mechanical Engineering from UKM in 1990. He then worked as an engineer before joining the Dept. of Mechanical and Materials Engineering, UKM and continued his studies in 1992. End of 1995, he received his PhD from University of Wales Swansea under the Mechanical Engineering Department and Institute of Numerical Methods in Engineering. Dr. Ahmad Kamal Ariffin teaches Mechanics of Materials, Computational Methods in Engineering and Finite Element Methods. His speciality is in computational method in engineering under the area of powder mechanics, fracture mechanics, friction, corrosion, finite element/discrete element and parallel computations. He is a Fellow of the Institute of Materials Malaysia, founder of Malaysian Association of Computational Mechanics and also member of International Association of Computational Mechanics (IACM).

K. Sopian is a Professor in Renewable Energy at the Department of Mechanical and Material Engineering and concurrently the Director of the Solar Energy Research Institute, a center of excellence for the research and development in solar energy technology at UKM. He obtained his BSc in Mechanical Engineering from the University of Wisconsin-Madison in 1985, MSc in Energy Resources from the University of Pittsburgh in 1989 and PhD. in Mechanical Engineering from the Dorgan Solar Laboratory, University of Miami in 1997.

A. Arifin is a lecturer at the Department of Mechanical and Materials Engineering, Universiti Kebangsaan Malaysia. He obtained BSc in Mechanical Engineering from Universiti Kebangsaan Malaysia (UKM) and MSc from University of Manchester Institute of Science and Technology (UMIST). His research interests are mechanical design, powertrain, and composite materials.

C. H. Azhari is a Professor at the Faculty of Engineering and Built Environment, at Universiti Kebangsaan Malaysia, she received bachelor's degree in Polymer Technology and was awarded a PhD in Response Engineering from Brunel University of West London in 1979 and 1985 respectively. Her specialty is in non-metallic materials processing, natural fibres, nanomaterials. She also serves as the Director of the Center for Corporate Planning and Communications at that university.

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