Composites Science and Technology 151 (2017) 52–61

Contents lists available at ScienceDirect

Composites Science and Technology

journal homepage: http://www.elsevier.com/locate/compscitech

Investigation on energy absorption of natural and hybrid fiber under axial static crushing

Zeid Fadel Albahash [a, b], M.N.M. Ansari [a, *]

[a] Department of Mechanical Engineering, Universiti Tenaga Nasional, Kajang 43000, Selangor Darul Ehsan, Malaysia
[b] Department of Mechanical Engineering, Kufa University, Iraq

ARTICLE INFO

Article history:
Received 28 January 2017
Received in revised form
28 July 2017
Accepted 29 July 2017
Available online 1 August 2017

Keywords:
Hand layup
Energy absorption
Jute fiber
Crash worthiness parameters
Crushing

ABSTRACT

Using metallic materials in vehicles structures increases cost and fuel consumption, therefore, the trends start to use cheaper and lite materials. Fibers are used in composites in automotive applications because they are lightweight, stiff, and stronger than bulk material, as well as achieve comparable energy absorption to metallic materials. The aim of this research is to investigate the potential of natural fiber in the applications of crash energy absorption. An experimental procedure (hand layup) was applied to investigate the effect of using jute fiber on crash worthiness parameter of composite material with other types of fibers such as Kevlar and glass fiber reinforced epoxy composite. The work involved fabrication the tubes using three layers, two geometries (circular and square) with three different heights at constant crush speed 1.5 mm/s. The results show that the tubes of jute fiber were ineffective and failed directly, but, replacing one layer of jute fiber by one layer of other types of fibers lead to an enhancement in crash worthiness parameters especially, failure type and crash worthiness parameters. The better results are achieved when using hybrid jute and kevlar, where the energy absorption is enhanced by 17.75% and the specific energy absorption is enhanced by 25.122% in case of circular tube with diameter 50 mm. In case of square tube with side length 50 mm, the results are enhanced by 62.764% for energy absorption and 58.942% for specific energy absorption.

1. Introduction

Most vehicle body frames are thin-walled steel columns. The rails at the front and rear body of cars are the main energy-absorbing parts in a crash. The bumpers of a vehicle may play a role for a minor frontal or rear impact, when the vehicle collides with a pole or a tree at a relatively low speed, such as in a car park [1]. Therefore, there is a need to enhance the energy absorption and control the mode of failure of thin shell tube made from composite material and use it instead of metallic materials in the structural parts of vehicles to provide more protection for passengers during accidents. Many studies have been done on that using different types of fibers, different geometries and using types of foams or fillers Ref. [1]. Ref. [2] used two configurations of E-glass/jute hybrid laminates (T and Q) manufactured from total fiber volume of 50± 2% (14 glass fiber layers + 4 jute fiber layers). The results showed that T-laminates have better residual properties but sudden failure of the jute fiber limits their use. Q-laminates showed good performance due to their high impact energies and ease of control. Ref. [3] used in their study a handmade lay-up E-glass/epoxy plain weave woven fabric composite cured in different processes such as air curing, vacuum assisted curing, and compression curing to test the statistical differences by theses processes. Ref. [4] found that using various or hybrid fiber types has a significant effect on the crush failure modes and crush energy absorption. Ref. [5] studied the crush force efficiency and crush strain relation that allows a homogeneous comparison of the structural response independently from the elastic properties of the material. Ref. [6] studied the crashworthiness of the square thin-walled tubes, to develop optimum structure of vehicles to ensure passengers safety during collisions.

Ref. [7] studied and evaluated the fracture toughness (G_{II}) behavior of carbon fiber epoxy composite reinforced with thermoset interleave and chopped Kevlar, For test, the researchers used five different types of carbon fiber/epoxy composites, Base laminate without interleave, unreinforced interleave, 0.5, 1.0 and 1.5 mg/cm2 chopped Kevlar fiber reinforced interleave. The results showed that

* Corresponding author.
E-mail address: ansari@uniten.edu.my (M.N.M. Ansari).

http://dx.doi.org/10.1016/j.compscitech.2017.07.028

fracture toughness G_{IC} of composites was improved significantly by interleaving and Kevlar reinforcement of carbon/epoxy composite. Thermoset interleave can improve G_{IC} of carbon fiber epoxy composite about two-fold, while short Kevlar reinforcement can improve it up to 1.5 times. Ref. [8] studied how progressive deformations of nine different geometrical shapes small-scale composite tubes were affected by geometry, dimension and triggering mechanism under quasi-static crushing [8]. Major constituents in a fiber-reinforced composite material are reinforcing fibers, and matrix that acts as a binder for the fibers. Coupling agents, coatings, and fillers may be found as other constituents. Coupling agents and coatings are applied to fibers to improve their wetting with the matrix, as well as to promote bonding across the fiber matrix interface. Both, in turn, promote a better load transfer between the fibers and the matrix. Fillers are used with some polymeric matrices primarily to reduce cost and improve their dimensional stability Ref. [9].

Epoxy resins dominate the aerospace composites market, especially the family of epoxy resins which compose 176.66 °C curing that enhances the results in laminates, which have unique mechanical properties. (Curing epoxies with Lower temperature (121.11 °C) and below), compared with vinyl esters, have static mechanical properties. Epoxy, compared with polyester and vinyl esters, has the highest values of fracture toughness, which may lead to increase the fatigue performance of the laminates. Another big difference is that the shrinkage of the epoxies is relatively low at about 3%, while vinyl shrinks about 8% during cure. Cracking during the cure of thick pieces of high curvature can be caused by high cure shrinkage of vinyl esters Ref. [10]. Hand lay-up, is an old, simple, labor intensive method for manufacturing low-volume composite. It is particularly suitable for large components such as boat hulls. Any reinforced material such as glass, mat, or woven roving is placed manually in the open mould, and then the resin is poured or sprayed on the reinforced material Ref. [11]. Woven roving should be used as an alternative to the layers of chopped strand mat. A combination of woven roving and chopped strand mat is presented by many suppliers to reduce the costs of labor and to prevent omitting of the chopped strand mat by mistake. Woven roving enhances the strength and rigidity of the mould, but it is difficult to get them out with resin, and they do not match easily with the shape of the mold Ref. [12].

Ref. [13] found that vacuum infusion (VI) is a good alternative to more traditional hand lay-up (HL) although it is costly, because it is clean and friendly work environment. Another advantage of VI over HL is the achieving of the prepregs level of resin, which leads to stronger and lighter laminates [13].

Material and structure errors can produce error in designing composite structures. Materials error commonly is related to error in analyzing the nature of the individual ply anisotropy, inaccurate evaluation of the damage in the material, and lack of identifying the environmental sensitivities.

There must be strain continuity through the thickness of the laminate, in which the level of stress that carried by every ply depends on laminate modulus. As a result, a significant decline in stress and internal shear stresses may happen between plies that are oriented at large angle to each other. Design errors may happen in composite material with high anisotropic coefficient of thermal expansion Ref. [14].

The effect of specimen thickness, impact or kinetic energy, and velocity of impact were studied by Ref. [15], and they observed damage for all impact energies. The brittle behavior of the fibers used to reinforce composites, and also the behavior of the resins used for the matrix phase caused partially this sensitivity to impact damage [15].

Ref. [16] studied fracture toughness and impact energy absorption for the fracture of epoxy–carbon laminates. The mechanical behavior under quasi-static loading conditions has been investigated by three bending tests. They found that the bending strength and the bending modulus under quasi-static and impact conditions increase with increasing the interlaminar fracture toughness. They also found that the initiation and propagation energies under impact conditions are affected by interlaminar fracture toughness [16].

Experimental data for braided (30/0/30) and CSM tubes were compared to the analyzed data of the model and the comparison results were encouraging. The behavior of the braided and continuous strand mat (CSM) glass fiber cylindrical tubes under quasi-static load was studied by Ref. [17]. They investigated and analyzed the behavior of circular cylindrical tube under near static crush conditions to understand the tube crush mechanism in different stages. To evaluate the energy absorption during tubes crushing, they introduced a mechanism based model [17].

Ref. [18] studied the effectiveness in crashworthiness parameters like the energy absorption and the deformation by using the modeling and numerical simulation for single, double and multi wall circular and square tube with and without aluminum foam under axial crushing loading. The foam-filled thin-walled square tubes are modeled as shell wherein, foam core is modeled by incorporating visco-elastic plastic foam model in Altairs RADIOSS. It is noticed that the multi-wall tube structure with foam core changes the distortion modes significantly and results in a considerable increment in energy absorption capacity in comparison with and without foam core. In addition, the multi-wall tube foam filled structure demonstrates mixed deformation modes because of the significant effect of stress wave propagation. A sum of three square and three circular tube designs are demonstrated under axial impact loading with single, bi-tubular, and multi-tube structure with and without aluminum foam for both sorts of tubes. The thickness for every tube was 2 mm and a length of 300 mm. Fig. 1 shows the simulated deformed and deformed-cut section of the empty square and circular tubes, respectively. Fig. 2 shows the simulated deformed and deformed-cut section of the square and circular foam filled tube, respectively [18].

In this paper, an axial quasi static crush test is applied to square and circular cross section using three types of fiber (Jute, hybrid Glass and Jute fiber, hybrid Kevlar and Jute fiber) with orientations (0/90°) and using three different heights, two diameters for the circular, and two sides length of the square tube, in order to obtain optimum design. The paper is organized as follows. Section 2 presents the methodology of the research. Section 3 shows the results and discussion, while conclusions are in section 4.

Right now, classical support materials, for example, glass and carbon file are progressively being substituted by advanced composite materials such as natural fibre-reinforced polymers (NFRP). It is predictable that utilization of fiber/polymer composites will extend sooner rather than later because of the high advantages of interest offered by these materials, for example, high strength, low weight and corrosion resistance Ref. [19]. Natural fibres, for example, jute, hemp, kenaf, Sisal and bamboo have been examined because of their mechanical properties and their potential use in composite materials. These common natural fiber-reinforced composites are discovering applications in the development structure manufacture, with an anticipated yearly US request increment of as high as 60% [20–22]. Investigations of common natural fiber-reinforced polymer (NFRP) have been achieved for specific geometric shapes of composite tubes that are fundamentally designed for the most automobile applications because of their low weight and good quality, and corrosion resistance [23–26].

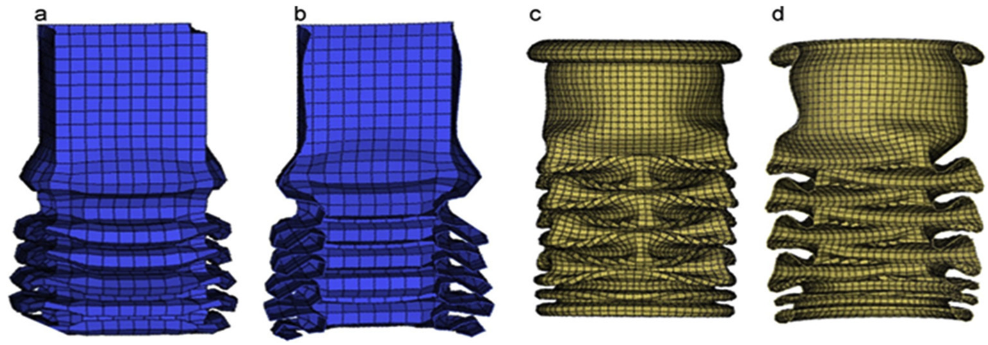

Fig. 1. Simulated deformed-cut section single tube [18].

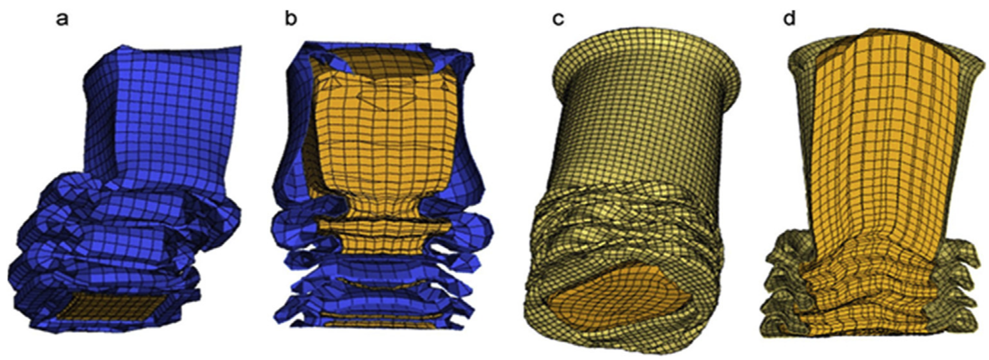

Fig. 2. Simulated deformed and deformed-cut section single tube [18].

2. Experimental setup

2.1. Geometry and materials

Thirty six (36) samples have been investigated with two geometries circular and square using two diameters for the circular and two sides length for the square. Three layers of fibers were used with orientation 0–90°. The tubes made from Jute fiber and hybrid fiber (Glass 200 and Jute, Kevlar and Jute). Epoxy is used in this experiment as a matrix as shown in Fig. 3.

2.2. Preparation of mandrels

After preparation of the materials, the second step started with preparation of the mandrels. Two geometries of mandrels have been used (circular, square), which were manufactured from wood in the work shop with 330 mm height, and (50 mm, 100 mm) for the diameter and side length as shown in Fig. 4.

The two parts of the mandrel were bound by a tape to prevent any movement. Then, the mandrel was covered by a layer of weak nylon or plastic to prevent the epoxy from sticking to the mandrel, which could affect the tubes through extraction as shown in Fig. 5.

2.3. Fabrication process

The oldest and simplest hand layup technique was used for fabrication. The reinforced material such as mat, or woven roving was placed manually in the open mould, and then, the resin was poured and sprayed on the reinforced material. After the completion of the first face, the rolling of the fiber was continued around the mandrel. The mold was left 24 h to ensure its dryness completely, and then, the mold was removed from the tube. Finally, the producing tube became ready for next process. Same procedure was used for hybrid tubes. After that, the tubes were cut into

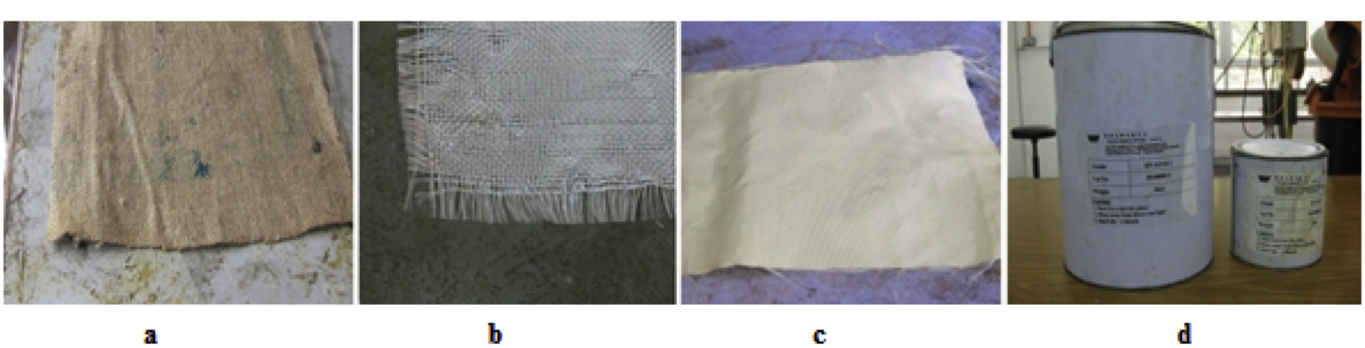

Fig. 3. (a) Jute fiber, (b)Glass fiber, (c) Kevlar fiber and (d) Epoxy.

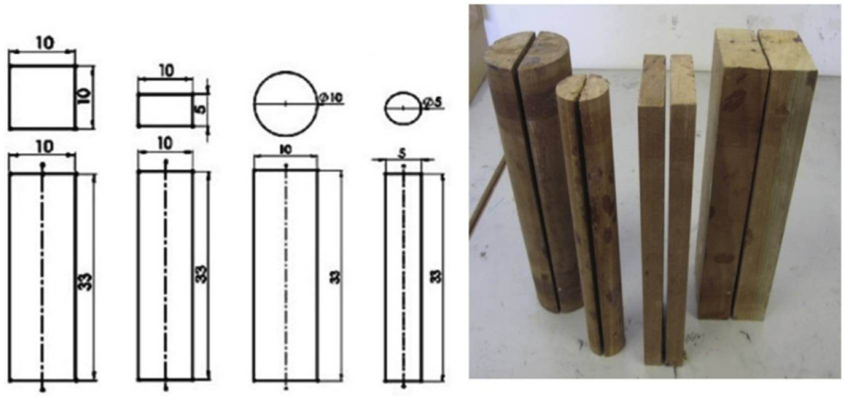

Fig. 4. Mandrels (core).

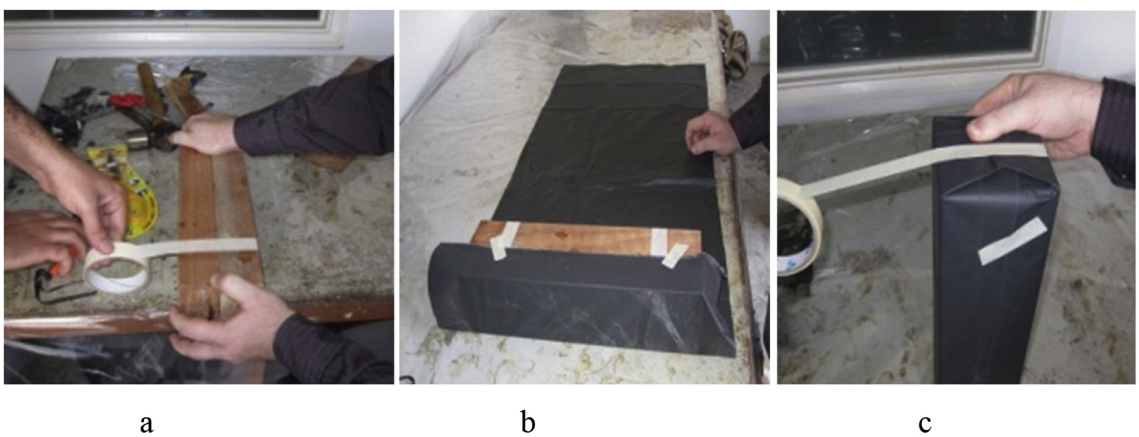

Fig. 5. Process of covering the mandrel: (a) binding the two parts by a tape, (b) cut one layer nylon, (c) covered the mold by nylon.

different heights (200 mm, 250 mm, 300 mm) by cutting machines. Fig. 6 shows the fabrication process procedure.

2.4. Labeling and weighing

The samples were weighed, and then, nominations were used for the specimens in order to identify them before and after the crush, where (L1, L2, L3) represent lengths of specimens (200 mm, 250 mm, 300 mm) respectively, J represents jute fiber, K represents the Kevlar fiber and H1 represents hybrid fibers of (2 Jute + 1 Kevlar), the G represents the Glass fiber and H2 represents hybrid fibers of (2 Jute + 1 Glass). C1 and C2 represent the circle diameters, which equal (50 mm, 100 mm) respectively. S1 and S2 represent the square side lengths, which equal (50 mm, 100 mm) respectively. The matrix (epoxy) was not symbolized because only one epoxy type was used.

2.5. Testing procedure

The specimens were subjected to a quasi static load using a computer-controlled servo-hydraulic INSTRON machine, system ID (4469 H2005) with scale load 100 kN to make crushing test at a speed of 15 mm/min. All the specimens were crushed with crushing distance of 80 mm. During the crushing test for each specimen, photos were taken for all stages of crushing in order to indicate the failure modes that could happen.

3. Results and discussion

3.1. Load displacement and failure modes

Failure of structure occurs when it cannot afford the applied load. Many modes of failure have been studied and investigated

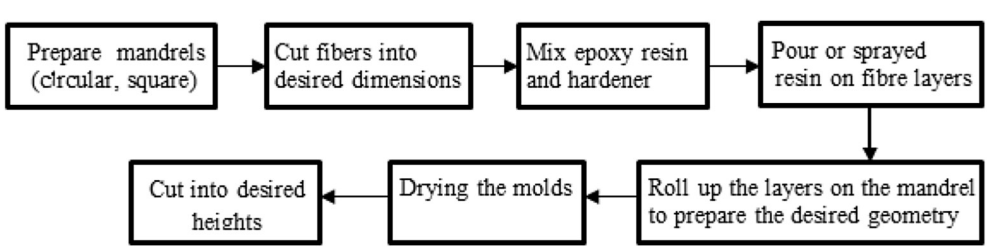

Fig. 6. Fabrication process procedure.

during the crushing processes of the tubes. The photos that were taken during the crushing test helped to investigate the failures, which occur in each specimen. The failure modes that have been found are:

3.1.1. Jute fiber

The tubes showed mostly same behavior, the load displacement curve increased from (0) kN until reaching maximum load values (17.56 kN–63.461 kN), which represent the same initial failure load, then the load decreased until it failed. The buckling and breakage failures were the most common failures noticed for the tubes that fabricated from jute fiber for both geometries. These failures happened because of jute fiber brittle behavior after solidification as shown in Fig. 7.

3.1.2. Hybrid fiber

Using hybrid fiber (one layer of (glass or Kevlar) +2 layers of jute) caused differences in the behavior of load displacement curve and the failure modes. Delaminating, buckling, micro cracking, splitting and splaying failures modes were most familiar for tubes of hybrid fiber.

Fig. 8 shows the load displacement curve for circular hybrid (Kevlar-jute) fiber/epoxy of 50 mm diameter and 300 mm height (C1H1L3). The load increases dramatically from 0 kN until it reached 28.86 kN at 6.535 mm displacement,Post-crushing zone started with dropping the load sharply from the maximum to 9.79 kN at 7.714 mm due to buckling failure on upper end tube. The structure resisted the crushing load causing an increase in the load until it reached 28 mm, then the load dropped slightly due to the continuation of buckling and splitting. The load was increased due to splaying failure and dropped dramatically due to splitting and delamination failure.

Fig. 9 Shows the manner of load-displacement curve of the square (Kevlar-jute) fiber/epoxy of (100 mm, 50 mm) width and 300 mm height (S1H1L3). The load increased sharply until it reached the initial failure and maximum load of 50.1 kN at 3.39 mm. The load was decreased in three stages. In the first stage, it decreased due to the buckling failure from maximum load until it reached 35.902 kN at 5.499 mm. In the second stage, the load decreased due to continuous buckling with cracking failure at lower half of the tube until it reached a 7.052 mm displacement. The third stage involved a decrease in the load with a slight fluctuation until it reached 54.603 mm displacement due to delamination and breakage, which occurred at the middle of the of the specimen. The test was continued until the end of the test at 800 mm.

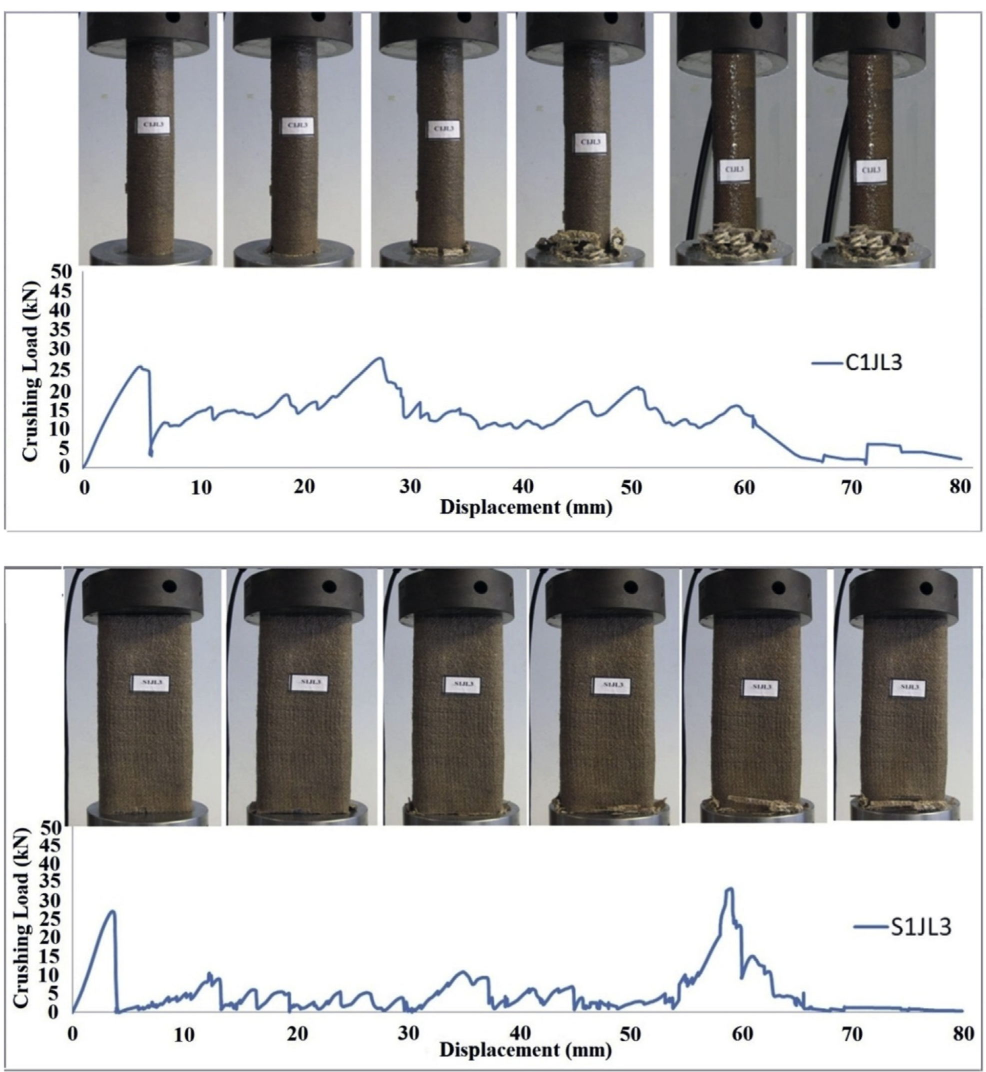

Fig. 7. Crushing process of jute fiber/epoxy.

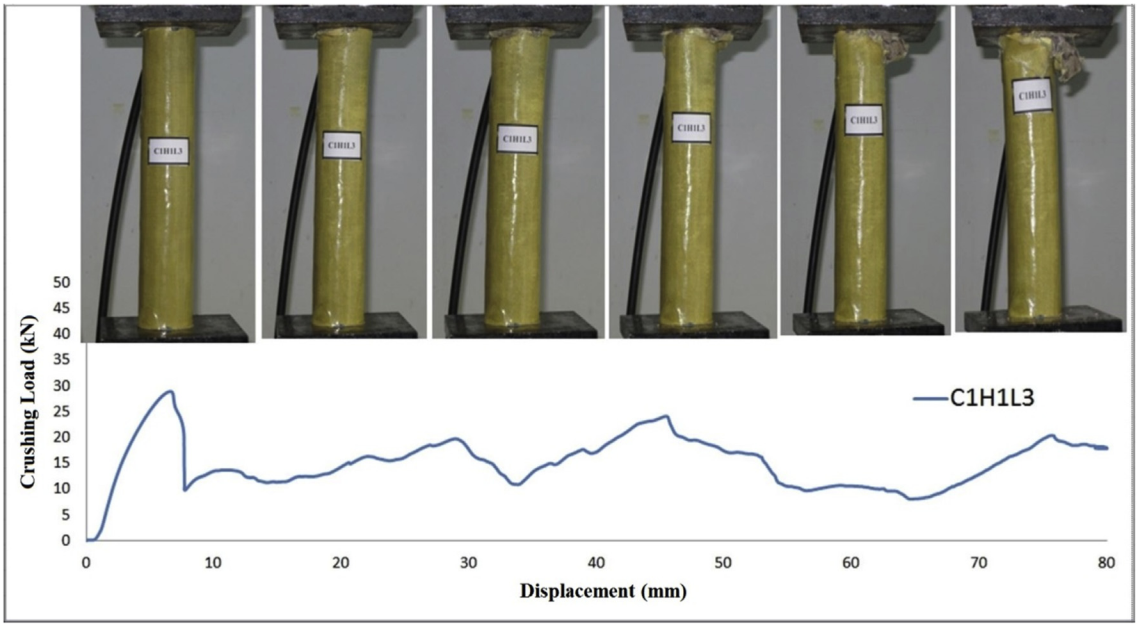

Fig. 8. Crushing process of circular hybrid (kevlar-jute) fiber/epoxy.

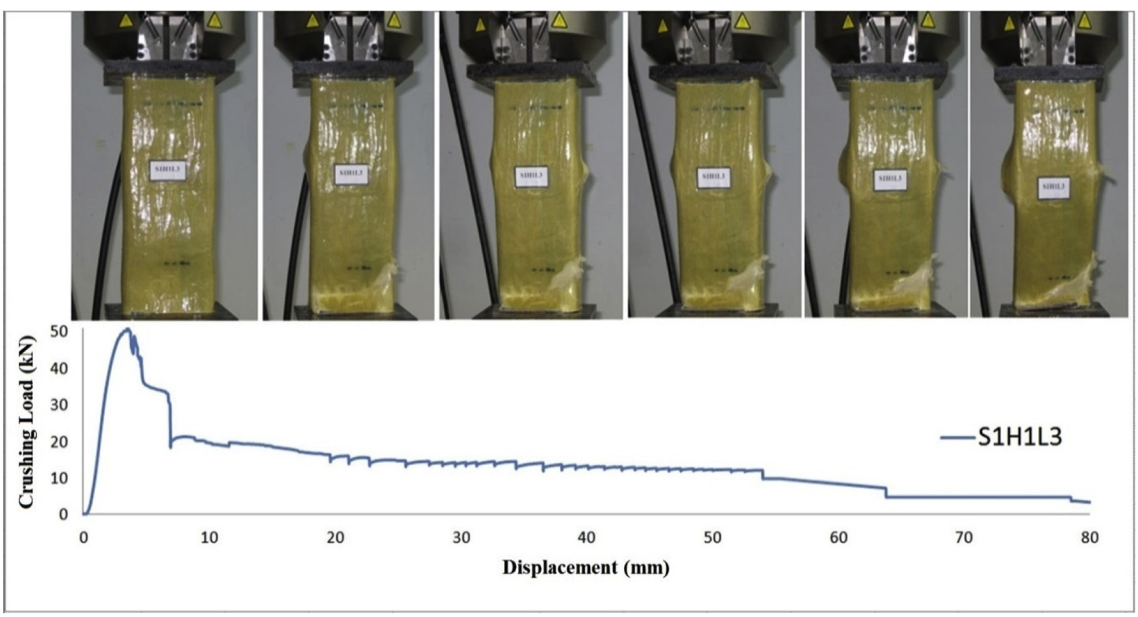

Fig. 9. Crushing process of square hybrid (Kevlar-jute) fiber/epoxy.

Fig. 10 shows clearly the load displacement curve for circular hybrid (glass-jute) fiber/epoxy of 50 mm diameter and 300 mm height (C1H2L3). The load increased sharply from 0 kN to 24.19 kN at 2.159 mm. This load value represents the initial failure load; pre-crushing zone limit ended with initial failure load. The load displacement curve dropped sharply due to micro cracking failure followed by cracking and splitting failure at upper end. The load then increased and fluctuated with a little dropping in some regions of the curve due to splaying failure with fiber breakage and splitting failure with the platen moving downward.

Fig. 11 Shows the behavior of the load-displacement curve of the square (glass-jute) fiber/epoxy of (100 mm, 50 mm) width and 300 mm height (S1H2L3). The load increased gradually until it reached the optimum and initial failure load at 24.869 kN at 3.73 mm. The load decreased with fluctuation until it reached a minimum value at 33 mm due to multi failure micro cracking, buckling and splitting failure. The load increased gradually until it reached 18.21 kN, then the load decreased dramatically due to splitting failure. The load rose from failure due structure resistance to failure, then the load dropped again due to splitting failure until it reached 80 mm displacement.

3.2. Crushing energy absorption parameters

The area under the curve illustrates the elastic and plastic zone, which represents the total energy absorption (TEA) of a tube during

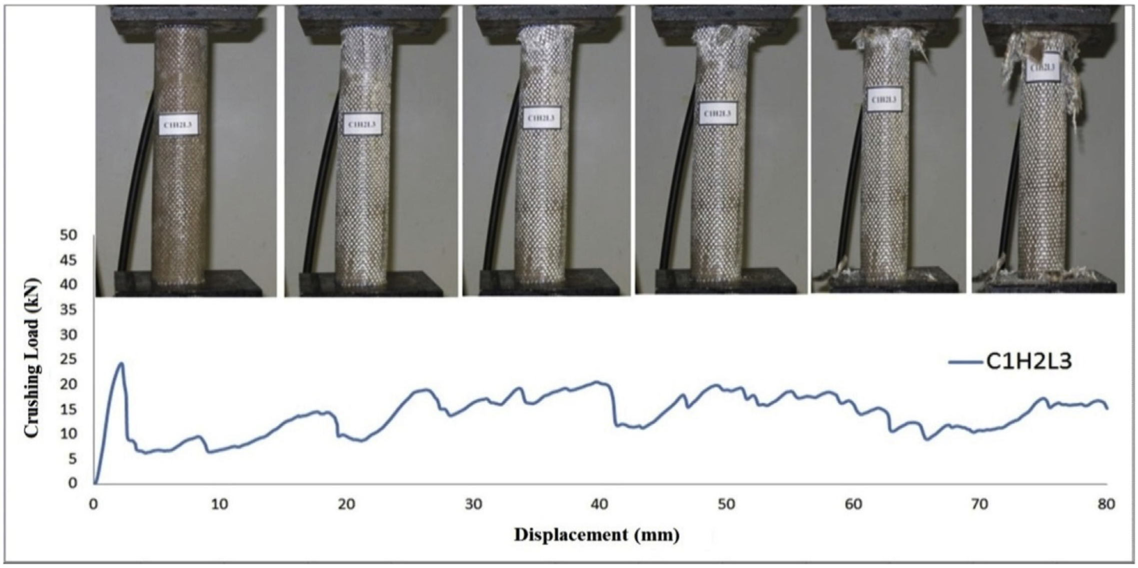

Fig. 10. Crushing process of circular hybrid (glass-jute) fiber/epoxy.

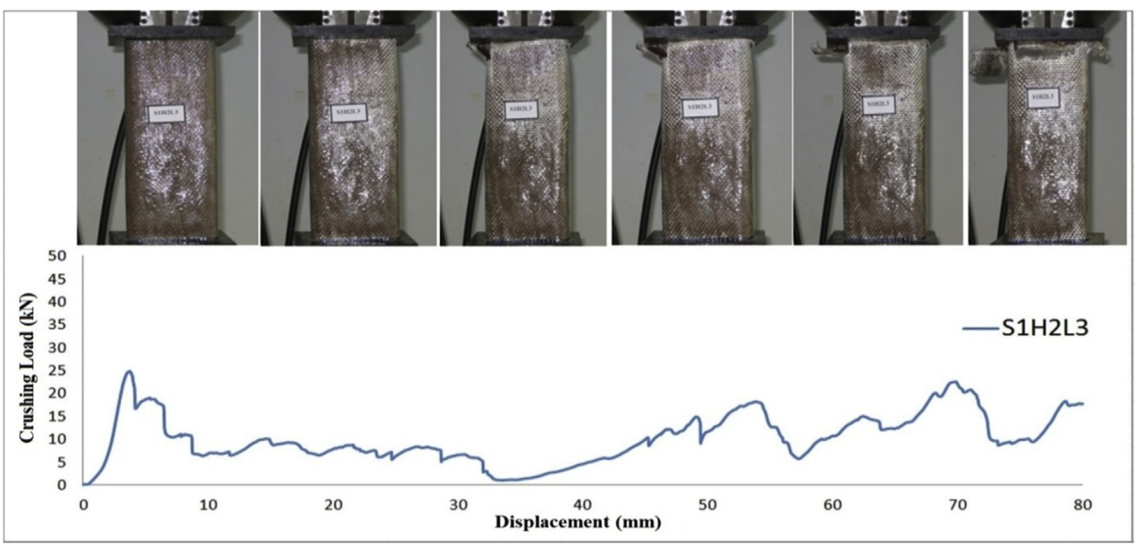

Fig. 11. Crushing process of square hybrid (glass-jute) fiber/epoxy.

crushing. This energy can be obtained by numerical integration of the load displacement curve. The crushing energy absorption can be calculated depending on many parameters as EA (kJ), SEA (kJ/kg), which are discussed below.

3.2.1. Energy absorption (EA)

Energy absorption can be calculated by finding the area under the load -displacement curve. The areas under the curve consist of two areas as shown in Fig. 12.

The first area represents the pre-crushing zone or elastic region which represents the triangle area, this area can be calculated using equation (1). where the height represents the initial failure load and the base represent the displacement of crushing until the initial failure load (Triangle Area Law):

$$EA\mathbf{1} = {}^{1}\!/\!_{2}*Fi*Di \tag{1}$$

where F_i in kN and D_i in meter then the REA in KN.m (KJ).

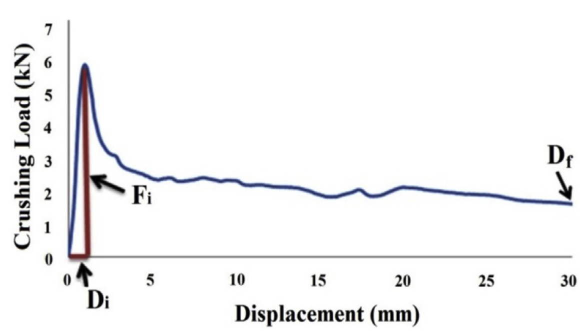

Fig. 12. Load displacement curve.

The second area represents the post-crushing zone or plastic zone, which can be calculated by using equation (2) [5]:

$$EA2 = \int_{Di}^{Df} F_i ds \Rightarrow EA2 = F_{avr}\left(D_f - D_i\right) \quad (2)$$

F_{avr} is the average failure load, D_i is the displacement until the initial failure load and D_f is the displacement until the end of crushing test. F_{avr} in kN, D_f and Di in metres so the energy absorption will be in kN.m (kJ).

According to [5], the total work during the axial crushing of a tube is equal to the area under the load-displacement curve. Therefore, the summation of the two areas gives the energy absorption under the load-displacement curve as shown in the following equation:

$$EA = EA1 + EA\mathbf{2} \quad (3)$$

This work shows that replacing one layer of jute fiber by Kevlar or Glass fiber enhances the results as shown in Fig. 13 and Fig. 14.

The results of TEA in Fig. 13 show that the jute fibre has achieved lowest value of TEA by both circular and square tubes for the three heights. The maximum value achieved by the circular tube (C2JL1) is 1.0906 kJ while the maximum value of the square tube (S1JL3) is 0.404 kJ. The replacement of one layer of jute fibre by glass or Kevlar enhanced the results significantly for all tubes geometries and heights. The hybrid H2 (Jute + Glass) fiber achieved higher results than the jute fiber but also showed unstable behavior for both circular and square tubes. The highest value of TEA for the circular tube (C2H2L1) is 1.3 kJ while the maximum value of the square tube (S1H2L3) is 0.719 kJ. The bigger circular and square tubes (C2H2, S2H2) showed unstable behavior compared with the smaller sizes as shown in Fig. 13. The highest and best stability is recorded for the hybrid H1 (Jute + Kevlar) fibre, where the circular tube (C1H1L3) achieved 1.194 kJ and (C2H1L3) achieved 1.355 kJ, while the maximum value of the square tube (S1H1L3) is 1.085 kJ. Fig. 13 shows that some values of TEA of the biggest diameter are higher than the small diameter for the circular tube of Jute or hybrid H2 fibre, however, the crushed tube mass during crushing process should be considered. Therefor, the SEA behavior should be studied.

3.2.2. Specific energy absorption (SEA)

Specific energy absorption is very important parameter, which can be calculated from equation (4) [5]:

$$SEA = \frac{EA}{CM} \quad (4)$$

where CM is the crushing mass in kg and EA is the energy absorption in kJ. The specific energy absorption can be enhanced by using materials of lowest mass and highest energy absorption. Fig. 14 shows the specific energy absorption (SEA) for the circular (C) and square (S) tubes.

It can be seen from Fig. 14 that highest and better stability results are recorded for the hybrid H1 (JUTE + KEVLAR) fibre where the smallest circular tube (C1H1L3) achieved 26.51 kJ/kg, while the bigger circular (C2H1L3) recorded 15.36 kJ/kg. The square hybrid H1shows the same behavior where the maximum SEA for the small square tube (S1H1L3) is 8.829 kJ/kg, and for (S2H1L3) is 5.726 kJ/kg. The hybrid H1 achieved best results because of splaying failure, which leads to increase the energy absorption and the specific energy absorption. The breakage failure occurs in most square tubes especially those made from Jute fiber.

4. Evaluation

To evaluate the research results, they are compared with other researches using glass (G) and Aluminum in circular and square geometries as shown in Table 1.

5. Conclusions

Thirty six specimens have been crushed statically using natural fiber, hybrid fiber with different geometries to investigate the effect of EA and SEA parameters on crash worthiness parameters. Based on the results acquired from this work, the conclusions can be summarized as:

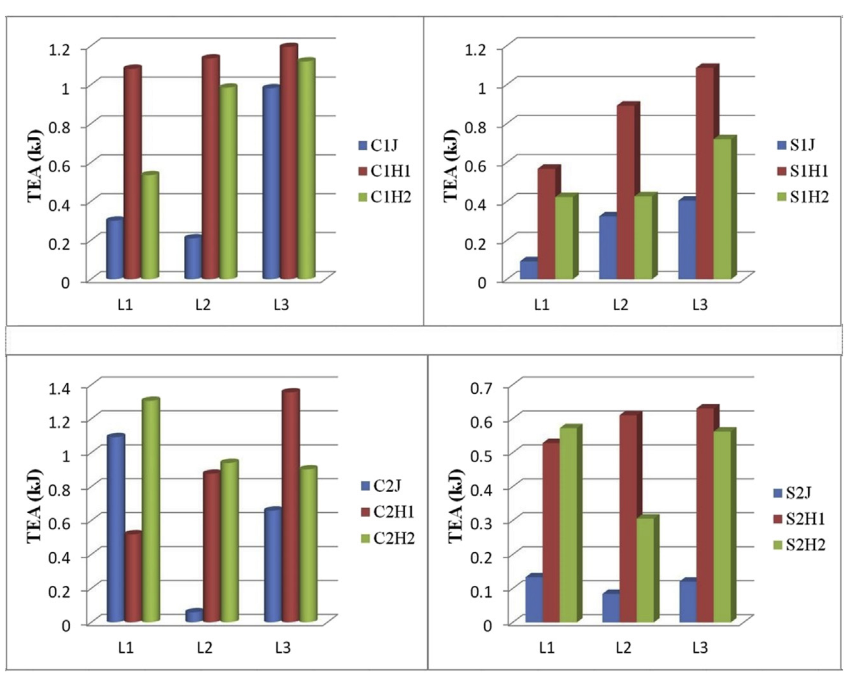

Fig. 13. Total energy absorption (TEA) of the specimens.

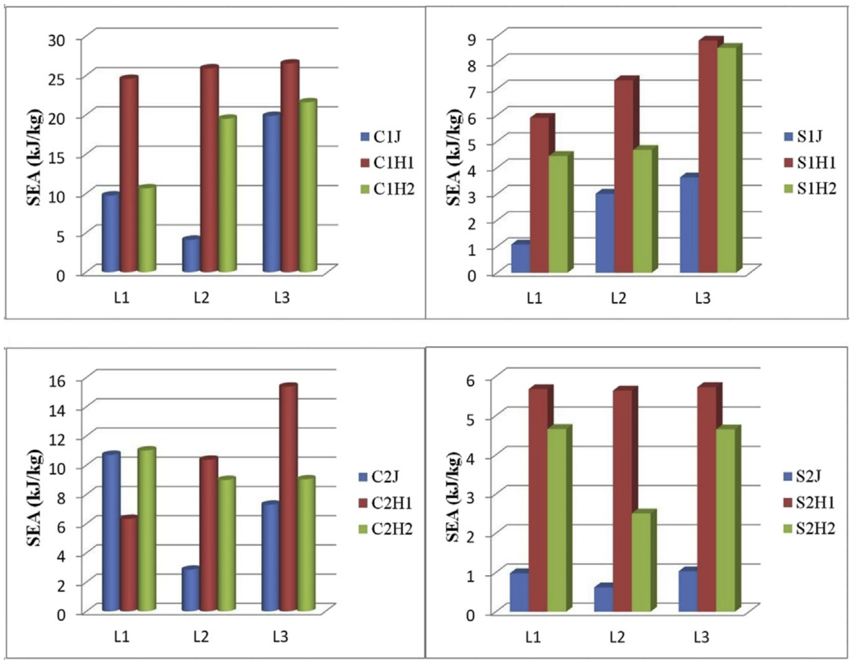

Fig. 14. Specific energy absorption (SEA) for the circular (C) and square (S) tubes.

Table 1
Comparison with other researches.

Research	Material	Geometry Circle	EA kJ	SEA kJ/kg	Geometry Square	EA kJ	SEA kJ/kg
Current Research	J + K	D 50 mm H 300 mm t 3.3 mm 3 layers	1.194	26.51	L 50 mm H 300 mm t 3.3 mm 3 layers	1.085	8.829
		D 100 mm H 300 mm t 3.3 mm 3 layers	1.355	15.36	L 100 mm H 300 mm t 3.3 mm 3 layers	0.63	5.726
	J + G	D 50 mm H 300 mm t 3.3 mm 3 layers	1.12	21.584	L 50 mm H 300 mm t 3.3 mm 3 layers	0.719	8.554
		D 100 mm H 300 mm t 3.3 mm 3 layers	0.901	9.02	L 100 mm H 300 mm t 3.3 mm 3 layers	0.562	4.65
[5]	G	D 100 mm H 140 mm t 6.3 mm	2.49	7.56			
[27]	G	D 25 mm H 1000 mm 1 layer	0.0266				
		D 30 mm H 1000 mm 2 layers	0.1156				
		D 35 mm H 1000 mm 3 layers	0.1551				
[18]	Aluminum	D 56.42 mm H 300 mm	0.4274		L 50 mm H 300 mm	0.4043	

It can be seen from the table that Ref. [5] achieved better energy absorption (EA) 2.49 kJ than the research 0.901 but with doubled thickness of glass. However, the research achieved better specific energy absorption (SEA) 9.02 kJ/kg. The research also achieved better EA than Ref. [27] with different diameters and thicknesses of glass. Moreover, the research achieved better EA than Aluminum in both geometries.

(1) The circular geometry is better than the square geometry in both failure modes and load displacement curve. (2) The jute fiber alone is ineffective, where it failed in brittle manner during the crush test for both geometry types (circular & square). (3) All parameters of crash worthiness are enhanced significantly by using hybrid fiber, which has been done by replacing one layer of jute fiber by one layer of (Kevlar or glass) fiber. (4) The results show that the height of 30 cm (L3) with (C1,S1) records better values than the two heights (20 cm and 25 cm) in case of comparing the hybrid fibre with jute fiber.

Acknowledgement

The authors would like to thank the Universiti Tenaga Nasional for their support and encouragement to complete this research. The authors also extend their grateful to the Iraqi Ministry of Higher Education and Scientific Research for their sponsorship to the research.

References

[1] G. Lu, T.X. Yu, Energy Absorption of Structures and Materials, first ed., Woodhead Publishing Limited, New York, 2003, 2003.
[2] I.M. De Rosa, C. Santulli, F. Sarasini, M. Valente, Post-impact damage characterization of hybrid configurations of jute/glass polyester laminates using acoustic emission and IR thermography, Compos. Sci. Technol. 69 (7) (2009) 1142–1150.
[3] A.F. Avila, D.T. Morais, A multiscale investigation based on variance analysis for hand lay-up composite manufacturing, Compos. Sci. Technol. 65 (6) (2005) 827–838.
[4] C.H. Chiu, K.H. Tsai, W.J. Huang, Crush-failure modes of 2D triaxially braided hybrid composite tubes, Compos. Sci. Technol. 59 (11) (1999) 1713–1723.
[5] H.S.S. Aljibori, I.A. Badruddin, A. Badarudin, W.T. Chong, Experimental study of composite structures in automotive applications, Int. J. Mech. Mater. Eng. 3 (1) (2008) 47–54.
[6] K.S. Lee, S.K. Kim, I.Y. Yang, The energy absorption control characteristics of Al thin-walled tube under quasi-static axial compression, J. Mater. Process. Technol. 201 (1) (2008) 445–449.
[7] S.N. Yadav, V. Kumar, S.K. Verma, Fracture toughness behavior of carbon fibre epoxy composite with Kevlar reinforced interleave, Mater. Sci. Eng. B 132 (1) (2006) 108–112.
[8] S. Palanivelu, W. Van Paepegem, J. Degrieck, J. Vantomme, D. Kakogiannis, J. Van Ackeren, J. Wastiels, Crushing and energy absorption performance of different geometrical shapes of small-scale glass/polyester composite tubes under quasi-static loading conditions, Compos. Struct. 93 (2) (2011) 992–1007.
[9] P.K. Mallick, Fiber-reinforced Composites: Materials, Manufacturing, and Design, CRC press, 2007.
[10] P.K. Mallick (Ed.), Composites Engineering Handbook, CRC Press, 1997.
[11] M.M. Schwartz, Composite Materials: Properties, Nondestructive Testing, and Repair, vol. 1, Prentice Hall, 1997.
[12] R.G. Weatherhead, FBR Technology Fibre Reinforced Resin Systems, first ed., Great Britain by Galliard (printers) Ltd, Prentice Hall INC, Great Yarmouth, 1980.
[13] G. Belingardi, M.P. Cavatorta, D.S. Paolino, Repeated impact response of hand lay-up and vacuum infusion thick glass reinforced laminates, Int. J. Impact Eng. 35 (7) (2008) 609–619.
[14] D.H. Kim, Composite Structures for Civil and Architectural Engineering, CRC Press, 1994.
[15] L.S. Sutherland, C.G. Soares, Impact tests on woven-roving E-glass/polyester laminates, Compos. Sci. Technol. 59 (10) (1999) 1553–1567.
[16] A. Pegoretti, I. Cristelli, C. Migliaresi, Experimental optimization of the impact energy absorption of epoxy–carbon laminates through controlled delamination, Compos. Sci. Technol. 68 (13) (2008) 2653–2662.
[17] S.C. Quek, A.M. Waas, J. Hoffman, V. Agaram, The crushing response of braided and CSM glass reinforced composite tubes, Compos. Struct. 52 (1) (2001) 103–112.
[18] M.D. Goel, Deformation, energy absorption and crushing behavior of single-, double-and multi-wall foam filled square and circular tubes, Thin-Walled Struct. 90 (2015) 1–11.
[19] Y.A. El-Shekeil, S.M. Sapuan, M.W. Algrafi, Effect of fiber loading on mechanical and morphological properties of cocoa pod husk fibers reinforced thermoplastic polyurethane composites, Mater. Des. 64 (2014) 330–333.
[20] A.K. Mohanty, M. Misra, L.T. Drzal, Surface modifications of natural fibers and performance of the resulting biocomposites: an overview, Compos. Interfaces 8 (5) (2001) 313–343.
[21] A. Le Duigou, C. Baley, Y. Grohens, P. Davies, J.Y. Cognard, R. Créach'cadec, L. Sohier, A multi-scale study of the interface between natural fibres and a biopolymer, Compos. Part A Appl. Sci. Manuf. 65 (2014) 161–168.
[22] Y. Li, Y.W. Mai, L. Ye, Sisal fibre and its composites: a review of recent developments, Compos. Sci. Technol. 60 (11) (2000) 2037–2055.
[23] R.A. Eshkoor, A.U. Ude, A.B. Sulong, R. Zulkifli, A.K. Ariffin, C.H. Azhari, Energy absorption and load carrying capability of woven natural silk epoxy–triggered composite tubes, Compos. Part B Eng. 77 (2015) 10–18.
[24] J. Holbery, D. Houston, Natural-fiber-reinforced polymer composites in automotive applications, JOM J. Miner. Met. Mater. Soc. 58 (11) (2006) 80–86.
[25] L. Yan, N. Chouw, Crashworthiness characteristics of flax fibre reinforced epoxy tubes for energy absorption application, Mater. Des. 51 (2013) 629–640.
[26] S.V. Joshi, L.T. Drzal, A.K. Mohanty, S. Arora, Are natural fiber composites environmentally superior to glass fiber reinforced composites? Compos. Part A Appl. Sci. Manuf. 35 (3) (2004) 371–376.
[27] A. Muhammad, ErcanŞevkat, Experimental and numerical study of energy absorption behavior of glass and carbon epoxy composite tubes under static compressive loading, IOSR J. Appl. Phys. 6 (4) (2014) 30–37.