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Energy absorption and failure response of silk/epoxy composite square tubes: Experimental

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ABSTRACT

This paper focuses on natural silk/epoxy composite square tubes energy absorption and failure response. The tested specimens were featured by a material combination of different lengths and same numbers of natural silk/epoxy composite layers in form of reinforced woven fabric in thermosetting epoxy resin. Tubes were compressed in INSTRON 5567 with a loading capacity of 30 kN. This research investigates the influence of the wall lengths on the compressive response and also failure mode of the tested tubes are analysed. The load–displacement behaviour of square tubes recorded during the test. Since natural woven silk has been used as textile in centuries but due to rare study of this fabric as reinforcement material for composites, the results of this paper can be considerable. Outcomes from this paper might be helpful to guide the design of crashworthy structures.

1. Introduction

As a part of engineering applications tubular structures offer a constant retarding force during the impact and constant deceleration through the entire stroke. In real applications, for example, in automobiles, the square tubes are not only energy absorbing members, but also serve as load-carrying structures.

The reason of widely use of axially crushed square tubes are their high specific energy and long stroke [1]. Meanwhile considering of fuel consumption reduction in automobile and aerospace industries attention is given to light weight energy absorber structures. For this requirement natural fibres are one of suitable candidates. Natural fibres exhibit advantageous properties as reinforcement for composites with low-density hence relatively light weight composite with high specific properties [2,3].

Among natural fibres, silk fibres are known as high strength and environmental friendly materials. Silk is a fibrous protein with unique physical and mechanical properties. Spiders (Arachnida) and insects (Insecta) especially silkworm are the best candidates of silk for research [4]. Silk has been used in form of textiles for many years. In advantages of silk it is important to remind that silk can be drawn to desired thickness and woven to a fabric form. Moreover in natural fibres comparison silk presents more resistance to moisture. It worth to noticing that silks from silkworms and spiders have impressive mechanical properties (Table 1), in addition to their advantages as environmental stability, biocompatibility, controlled proteolytic biodegradability, morphologic flexibility [5,6]. As it is shown in Table 1 silk with low density is a capable material to result a good value of specific energy absorption in composite structures compare with other synthetic fibres. The high value of elongation at failure caused silk composite square tubes performed a ductile behaviour in compression tests.

The motivation of this research is rare information of silk fabric as a reinforcement material in composites structure. Results focused on silk/epoxy square tubes energy absorption capability and failure modes.

2. Crashworthiness aspect of energy absorbers

Crashworthiness defined as the resistance of a vehicle to protect its occupants from serious injury or death in accidents [10]. Therefore, it counts as an essential parameter for vehicles and aircrafts design and due to its importance, it has been a topic of researches for engineers and scientists over the years [11]. In abroad range of automotive and aerospace applications collapsible impact energy absorbers as structure elements made of fibre reinforced composite materials are used [12,13]. The load-carrying capacity can be evaluated from the following two load levels:

- Initial crush load: The initial crush load can be obtained directly from the load–displacement response.
- Average crush load: The average crush load can be obtained by averaging the crush load values over the crush displacements through the post-crush region.

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Table 1
Mechanical properties comparison of some natural and synthetic fibre.

Material	Density (g/cm^3)	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at failure (%)	Source
B. mori silk	1.3–1.38	650–750	16	18–20	[7]
Spider silk	1.3	1300–2000	30	28–30	[8]
Flax	1.5	345–1035	50	2.7–3.2	[9]
Hemp	1.48	690	70	1.6	[9]
Jute	1.3	393–773	26.5	1.5–1.8	[9]
Coir	1.2	175	4.0–6.0	10.0	[9]
Sisal	1.5	511–635	9.4–22.0	2.0–2.5	[9]
Cotton	1.5–1.6	287–597	5.5–12.6	7.0–8.0	[9]
E-glass	2.7	1200	73	2.5	[9]
Carbon	1.8	4000	235	2	[9]
Kevlar 49	1.44	3600–4100	131	2.8	[8]

The primary data, which is obtained from a quasi-static crushing test, is the load versus displacement curve. A schematic representation of such a curve for a composite specimen is shown in Fig. 1 where three separate stages are highlighted. The first stage is the pre-crush response of the specimen terminated by the initiation of failure in the material. In the second stage region the post-crush stage, failure spreads across the entire specimen, which is characterised by the average crush load. Finally, in third stage the specimen compacts and the load increases sharply until the end of the test.

From the load–displacement response of the composite specimens the crashworthiness parameters can be obtained which are useful in comparing different composite materials and structures regarding their load-carrying capacity and energy absorption capability. Load–displacement diagrams analysed the crashworthiness characteristics with respect to the following important parameters:

- Maximum load which generally defines as peak load, P_{max}.
- Absorbed crash energy E which is referred to the area under the load–displacement curve.
- The post-crush displacement, δ, is total displacement of crushed specimen in load–displacement curve.
- Specific absorbed energy (SAE) is defined as the absorbed crash energy per unit of the crushed specimen mass.
- Average crushing load, $\overline{P}$, obtained by the following equation, when the load and post-crush displacement are defined as δ and P respectively:

$$\overline{P} = \frac{1}{\delta}\int_0^{\delta} P d\delta \tag{1}$$

- Crash force efficiency, CFE is the ratio of the average crushing load, $\overline{P}$ to the peak load, P_{max}.
- Stroke efficiency, SE, defined as the post-crush displacement, δ to the total length of specimen, L.
- Maximum compressive strength, σ_{max} defined as the peak load, P_{max} to square tube cross section area, A.

3. Materials and methods

3.1. Materials

Woven silk fibre having a count of 30 × 40 yarns (30 yarns in wrap or longitudinal direction and 40 yarns in weft or transverse direction) per centimetre was used as reinforcement in epoxy resin. The weight of fabric used is approximately 66 g/m^2.

3.2. Quasi static experimental test

Testing machine stopped in the tests referring to Figs. 3–5 in the beginning of the compaction zone since from then only compaction is happening.

Compressive tests were carried out on square cross-section specimens, consisting of 12 plies number of silk woven fabric and epoxy resin and various lengths (L), approximately equal to 50 mm with internal tube dimensions equal to 80 × 80 mm and radius (R) of curvature 5 mm at the tube corners as depicted in Fig. 2. All specimens fabricated by wrapping of the fabric with resin over a mandrel. The thicknesses (t) of the tested tubes with 12 layers silk/epoxy were equal to 1.7 mm and different lengths (50 mm, 80 mm and 120 mm).

Static axial compressive testes performed by INSTRON 5567 universal test machine with 30 kN loading capacity. The tests were in quasi-static conditions at constant cross head speed equal to 20 mm/min.

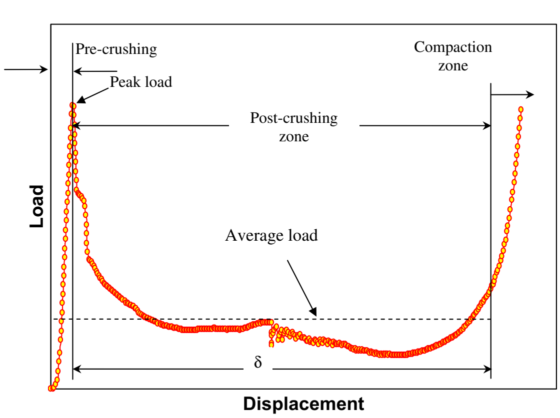

Fig. 1. Typical load–displacement curve.

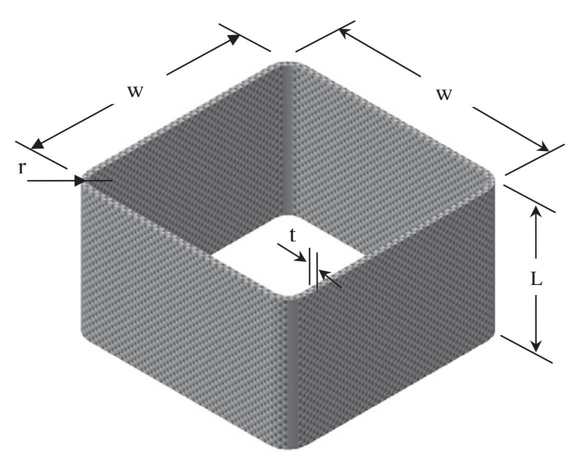

Fig. 2. Square silk/epoxy tube.

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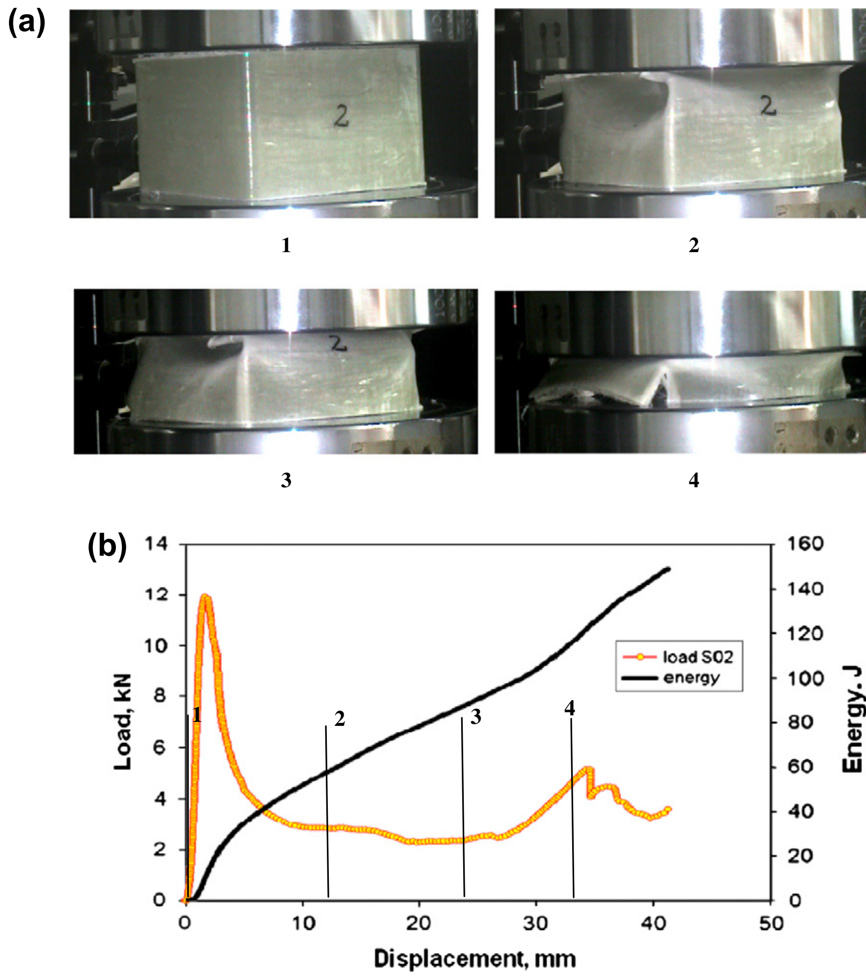

Fig. 3. Axial compression test of silk/epoxy square tube with 50 mm length, (a) photographs of different steps of compression test (b) combined diagram of load P, and crash energy absorption E, variation during the test. The sequential number of each picture marks the point of the two curves corresponding to the photographs.

Load–displacement curves recorded during the test by universal test machine. The load carrying capacity and the energy absorption capability of the square tubes were studied by computing the crashworthiness parameters from the load–displacement relations. The crushing history and the failure modes of the specimens were studied using the load–displacement relations and photos of compression test steps. Photographs have taken in different stages of crushing tests.

4. Results

Load–displacement curves of silk/epoxy composite square tubes resulted from compression test with 12 layers of silk/epoxy composites in different lengths (50 mm, 80 and 120 mm) presented in Figs. 3–5.

Combined diagrams of load–displacement curve and energy are indicated in Figs. 3b–5b. According to the load–displacement curves, tubes behave linearly first and the axial load is absorbed as elastic strain energy in the material. The tube walls then crushed either from top side, half or bottom side of square tubes due to the absorbed energy exceeds the threshold of materials properties at the crush zone. This leads to a sharp drop in the load, which exceeded half of the initial crushing failure load (P_{max}).

At this instant, Figs. 3b and 4b present that, the load drops down by local buckling from the top end of square tube and initiating cracks in bottom end of tube. This dramatically load dropping in Fig. 3b is associated with crack propagation and stiffness of the crush zone until the lamina bundles fall down. Remarkable decrease in load in Fig. 5b presents mid length buckling with failure starting in composite square tube failure from half of the length of tube.

Photographs present the steps of deformation and cracks formation in the tubes and were taken at various steps of the compression during the testing of the square tubes. The sequential number of each picture marks the points of the two curves corresponding to the photographs. Photographs in Figs. 3a and 4a are correspond to the local buckling while Fig. 5a is presenting mid length buckling in 12 layers of silk/epoxy composite square tubes compression test with different number of lengths of 50 mm, 80 mm and 120 mm.

5. Discussion

5.1. Failure mechanism

Based on the fact that woven fibre composites present higher energy absorption than the continuous or discontinuous filament composites [14].

Silk/epoxy tubes were found to crush in modes slightly different than those observed in synthetic composite structures. For brittle composite materials such as glass and carbon composites based on epoxy resin, the crushing process is a cyclic process of

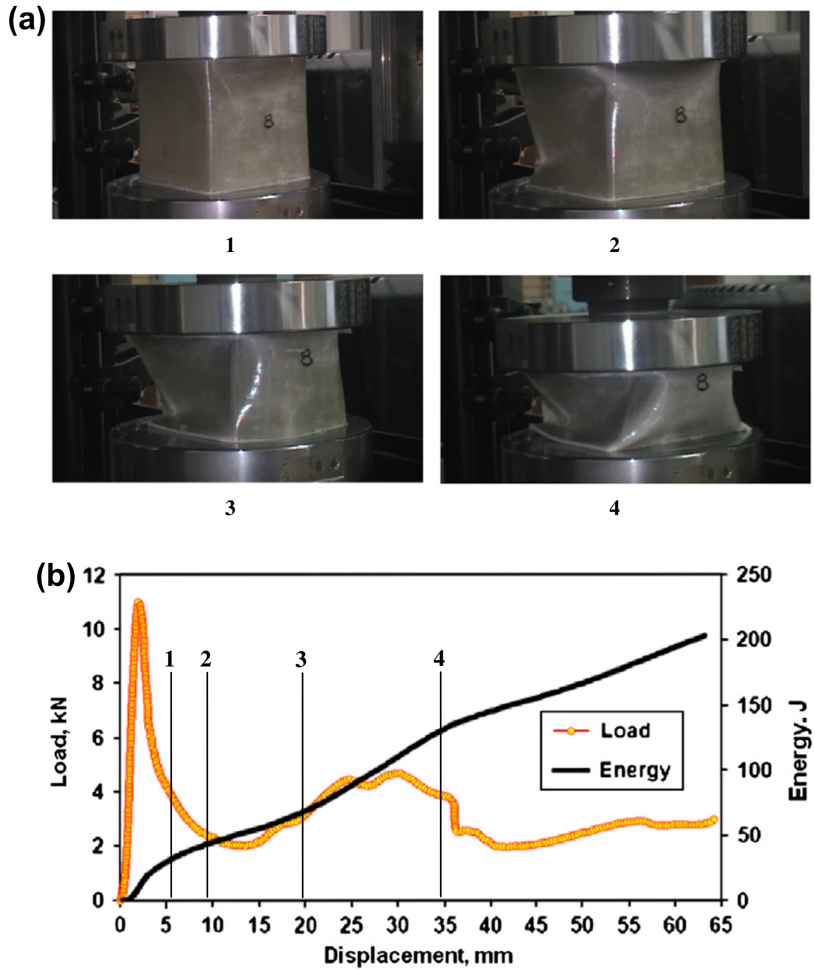

Fig. 4. Axial compression test of silk/epoxy square tube with 80 mm length, (a) photographs of different steps of compression test, (b) combined diagram of load *P*, and crash energy absorption *E*, variation during the test. The sequential number of each picture marks the point of the two curves corresponding to the photographs.

interlaminar cracks propagating between layers in crushed region of the tube forming lamina bundles [15]. For the metallic tubes, the crushing process is a process of plastic deformation [16]. Silk/epoxy composite square tubes in compression test presented a ductile deformation without debris splitting after being crushed.

In general, the failure modes observed during compression tests were unstable local buckling and mid length buckling and affected by the geometry of the silk/epoxy square tubes in term of lengths of the composite square tubes. According to previous researches, the nonlinear energy absorption response suggests that care must be taken in selecting specimen geometry for energy absorption characterisation studies [17]. Present research indicates that 50 mm tubes resulted higher specific energy.

In the initial stages of compression, load–displacement curves showed a significant drop in load after reaching to the peak load. This phenomenon referred to catastrophic failure. Accordingly, high peak crush failure load leads to catastrophic failure mechanism at initial failure crush stage, which results in low crush force efficiency (CFE) at post-crush stage as well as unstable load–displacement behaviour [18]. However, as it has been mentioned in some researches significant energy can also be absorbed when structural elements catastrophically fail [19].

Utilising compression test photographs helped to understand the modes of failure which indicated as local buckling and mid length buckling. Local buckling presented in Fig. 3 for specimens with 50 mm length (short length) and same failure mode has been shown in Fig. 4 for specimens with 80 mm length (mid length) and 12 plies of silk/epoxy composites. This failure mode is initiated at the top end or bottom end of square tubes. As deformation proceeded further, the cracks formed and propagated along the corners of tube hence crushing take place at low resistance therefore tube walls bent followed by catastrophic failure.

Silk/epoxy composite square tubes in 120 mm length exhibited mid length buckling which was failure initiated at the mid of the tube length which then proceed to overall tube buckling followed by catastrophic failure. This failure clearly has shown in Fig. 5. Mid length buckling in the compressed specimens is featured by ductile fracture and unstable collapse of the compressed tube, which starts with fracture of the square tube composite laminate at a distance approximately equal to its half the tube length. This phenomenon is clearly presented in Fig. 5. This figure performs a significant reduction of the compressive load after reaching to the peak load followed by tube catastrophic failure and cracks formation in the tube's corner edges. Cracks along the corner edges and circumferential fracture of tube at the tube caused low resistance of the compressed tube hence tube walls bent.

It is worth to mention that, silk/epoxy composite tube in Fig. 4 in compression tests demonstrates first and second peak loads. The same as other tested samples, this tube performed significant reduction of the compressive load immediately after load–displacement curve reached the maximum load in region of the crush zone. Away from this zone rest length of tube has remained with less damaged and almost it looks like as a shorter square tube. Hence with continuing the deformation second peak load was

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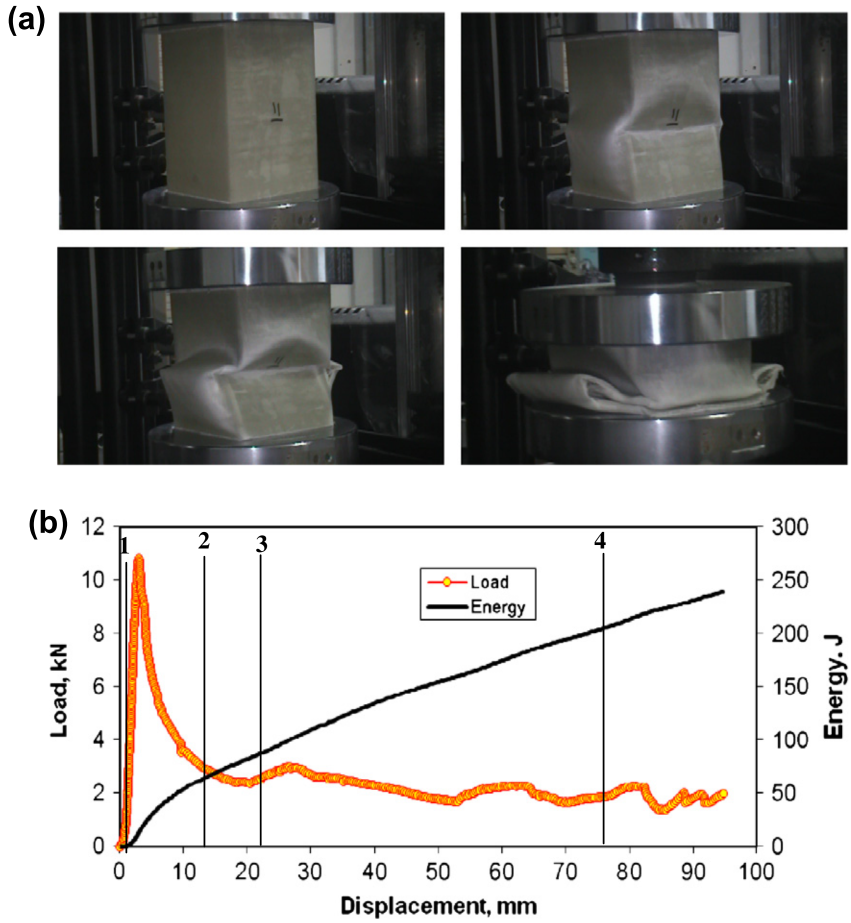

Fig. 5. Axial compression test of silk/epoxy square tube with 120 mm length, (a) photographs of different steps of compression test, (b) combined diagram of load P, and crash energy absorption E, variation during the test. The sequential number of each picture marks the point of the two curves corresponding to the photographs.

observed when the load reached to the second maximum, thereafter load dropped to the lower value until the compaction zone.

5.2. Crashworthiness characteristics

In Figs. 6–9, the crash load/energy absorption characteristics of the tested composite square tubes namely peak compressive load (P_{max}), average compressive load ($\bar{P}$), absorbed crash energy (E), specific absorption energy (SAE), crush force efficiency (CFE) are presented. Error bars denote the standard deviations of specimens with same geometrical characteristics. Errors indicate the variety of data for specimens in the compression tests.

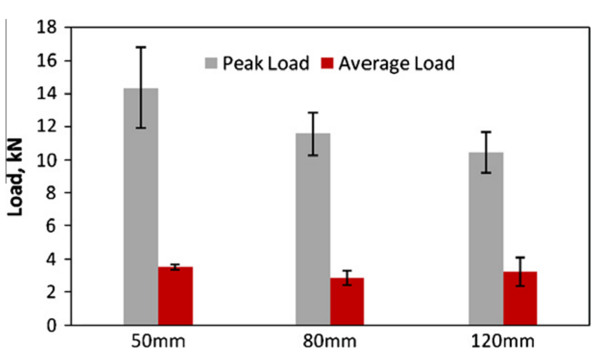

Fig. 6. Peak and average load characteristics for composite square tubes (error bars denote standard deviations).

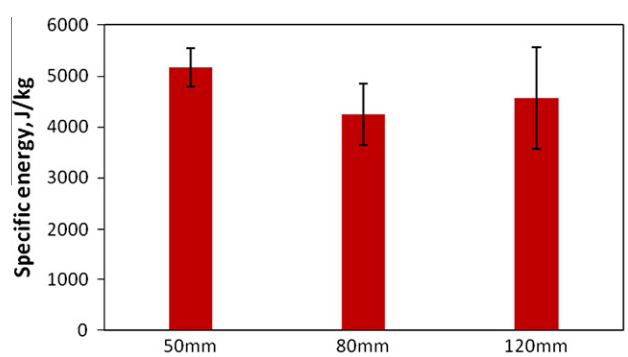

Fig. 7. Specific energy, SAE for silk/epoxy square tube specimens (error bars indicate standard deviations).

5.3. Peak and average load

Each load–displacement curve shows the history of crushing for related tube. Crushing started at a critical value which is called peak load, and then the deformation continued along the tube. Catastrophic failure is presenting with high peak load followed by dropping off quickly hence the average load is low. Information from load–displacement curves in Figs. 3b–5b directly showed maximum load (P_{max}) in silk/epoxy composite tubes during compression tests. Average compressive load ($\bar{P}$) for each tube was calculated from load–displacement curve related to the tube. Results

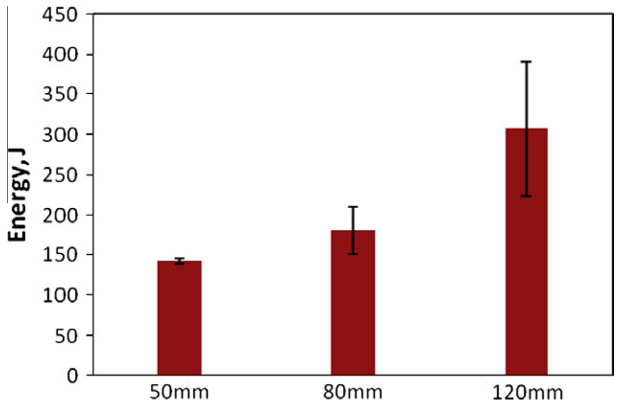

Fig. 8. Total absorbed crash energy, *E* silk/epoxy square tube (error bars denote standard deviations).

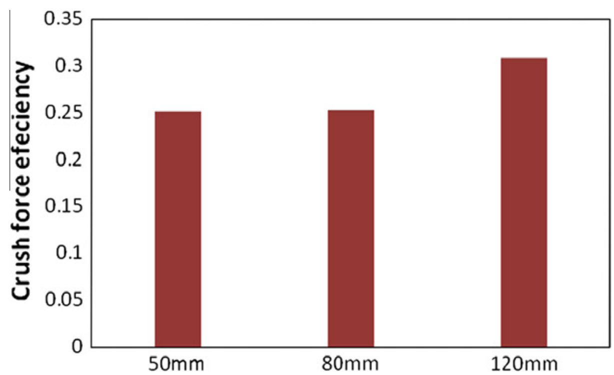

Fig. 9. Crush force efficiency CFE characteristics for silk/epoxy composite square tubes (error bars denote standard deviations).

have been indicated in Fig. 6 for silk/epoxy composite tubes with different lengths.

Decrease peak load associated with raising the lengths of composite laminates clearly indicated that, the length of tube walls of the tested specimens influence significantly on peak load value.

As sum up, results showed specimens with shorter length performed more resistance in compression test with performing higher value of peak and average load. Previous researches mentioned that peak load is depend on the geometric and material characteristics of the tested specimen for instance Farley and Jones [19] and Hull [20].

5.4. Crash specific energy capability and energy absorption

Results for specific energy in Fig. 7 cleared decrease in the length of silk/epoxy square tubes has a direct effect on increase the specific energy. It worth to mention axially crushed thin-walled square tubes have been widely used as energy absorbers because of their high specific energy absorption capacity and long stroke [1].

The value of energy absorption capability of a structure is depended on the area under the load–displacement curve [21]. Energy absorption characteristics of silk/epoxy composite square tubes calculated from load–displacement curves according to the length of tubes have been shown in Fig. 8. Consequently square tubes with higher value of average crushing load showed higher value of energy absorption.

Results remarked that the capability of energy absorption of silk/epoxy square tube is depended on the geometry of tubes. Tubes with higher length are able to absorb more energy which is due to absorbing more energy by their long length until end of crushing.

In the other word, energy is the area under load-deformation curve hence it is depended on average load and the distance of post crushing zone. Thus longer tubes absorb more energy in crushing due to their longest distance in post crushing zone. It is important to consider that the effect of tubes' length can be eliminated by comparing specific energy for tubes.

5.5. Crush force efficiency

Another important measure of crush performance is the crush force efficiency, which is defined as the ratio of the mean crush average load to the initial crush failure load. In order to evaluate the crashworthiness of energy absorber device, attention should be directed to its crush force efficiency (CFE) [22].

The diagram depicted in Fig. 9 includes the crush force efficiency (CFE). In silk/epoxy composite square tubes once the crush started, load dropped significantly and collapse continues with low value load. The ratio of average load and peak load is a considerable value to presents the failure mechanism of composite namely catastrophic or progressive failure. In contrast with progressive failure, catastrophic collapse mode is defined by the lower values of the crush force efficiency, which shows a high value of load as peak load and an average load throughout the compressive test. Obtained results presented low value of the crush force efficiency which is from 0.25 for 50 mm and 80 mm square tubes and 0.30 for 120 mm tubes.

6. Conclusion

Though silk is extensively used as a valuable material in textiles, the studies on silk-reinforced epoxy laminates are meagre thus this paper attempted to achieve a better understanding of energy absorption of natural woven silk fabric in form of square tube.

Natural silk/epoxy has used as energy absorber and measuring silk/epoxy square tubes crashworthiness characteristics. Specimens' crashworthiness parameters analysed and displayed highest peak load in the short length tube. The considerable difference between peak load and average load in all specimens results low amount of crash force efficiencies which means catastrophic failure in the square tubes subjected to the compressive load.

The most energy absorbed by the longest and thickest square tube which took longer time to reach the compaction zone. The other important parameter for an energy absorber is specific energy. Square tubes samples performed the highest specific energy absorbing in the short length tubes.

Based on results obtained by this research silk/epoxy by 12 layers laminate is not strong in comparison to other conventional energy absorbers. This research is a primary attempt of using silk as energy absorber. Authors are working on different lay up of laminate in order to obtain the critical thickness. Results will be sent to published.

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