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Influence of Geometric Shape on the Deformation Performance of Natural Jute/Epoxy Specimens under Axial Quasi-Static Compression

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Abstract
The interest in the using of natural composite has been increased significantly in recent years in many application of life due to their distinctive characteristics these like low density, high-energy dissipation ability, and fatigue resistance. Indeed, a seemingly good alternative candidate to metals.This work displays the deformation performance of two different types of geometrical natural composite shapes when subjected to uniaxial quasi-static loading. The purpose is to study the effect of geometrical on the progressive collapse of composite specimens. Two geometrical composite tubes have been fabricated by combination technique of manual lay-up and vacuum bladder moulding. The two types of the proposed tubes, which are the circular and corrugated shape. The experimental work was performed by using bidirectional jute fabric (with 3 layers and 100mm in length) and epoxy resin. Six patterns (three for each one) were tested and evaluated in the same conditions to provide a proper means of comparison between different geometric shapes. The result exhibited both kinds of samples demonstrated stable and progressive deformation with acceptable repeatability during the test process. It also showed the ability to absorb the higher energy of the corrugated samples configuration than the circular samples. Overall, the corrugated pattern configuration can be considered the optimal for crashworthiness structure application compared to a circular composite sample.

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1. Introduction:

Crashworthiness and occupant protection have become a significant issue in the many fields of engineering applications especially in automobiles industry [1]. Crashworthiness characteristic is defined as a measurement of the structure ability to maintain its passenger compartment in a survivable collision and reduce property loss when subjected to accident occurrence [2]. Crashworthiness has

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received much interest, mostly to assess the deformation behavior and the energy dissipation efficiency of diverse Thin-walled hollow tubes. It involves energy absorption by a controlled failure manner that enables the sustainability of a stable load-time profile and maintains a gradual decay in the load profile during the post-crushing stage [3]. The main purpose is to reduce the maximum acceleration on occupants to tolerance limits that are applied to the structure. Thereby preventing human and property casualties [4].

Reduction of weight and elevated energy absorption is the major factor in many applications as in aviation and vehicles industries field. In fact, the need to lower weight and improve energy absorption of vehicles have directed the authors' interest toward employ the composite tubes as a collapsible absorber [5]. As a result, composite material structures are lightweight, can be custom made in shape and composition, and can lead to good crashworthiness when utilized as energy absorbing device [6]. Furthermore, a decrease in weight by 100kg leads to fuel economy of approximately 0.35 l/100 km and reduces carbon dioxide emissions by 8.4 g /km, without a change in acceleration and elasticity values because of the lower weight [7]. Therefore, in recent years most researchers are encouraging the utilize composite materials instead of the classical metal materials to meet the above criteria, which can often come from either synthetic or natural reinforced fibers [8]. Synthetic polymers composites like carbon and glass fibers reinforced plastic have been vastly used in engineering application due to their good mechanical characteristic and lightweight [9]. However, due to increasing environmental concern in recent years, composites that are eco-friendly and which have the ability to decompose and be recycled are strongly preferred compared to synthetic reinforced fibers [10]. On the other hand, the common properties of natural composite materials such as low weight, abundant availability, low fabrication cost and good stiffness/weight and strength/weight as well as the ability to absorb energy well make it effective materials comparable to synthetic composite materials As an alternative.. Natural fibers such as kenaf, Jute, hemp and bamboo have been researched for their mechanical characteristics and their possibility of employment in composite materials. These natural polymers are finding implementation in the engineering industry, with projected demand growing as high as 60% [11] .A clear overview of the previous reports indicate that higher energy dissipation can be obtained by means of progressive crushing behavior, which mainly based on fibres mechanical characteristic, fibres volume fraction, stacking sequence of laminate, ply orientation and the tube geometry [12]. However, different stages of energy absorbing can be yielded by altering the geometrical with maintaining the same other parameters of the composite structures [13]. Accordingly, the main question arises about the geometrical and variables that can give the above requirements of the composite structure. Therefore, the quasi-static test was selected in this work. The merit of this procedure is to eliminate designs that show non-uniform or catastrophic failure; furthermore, depending on the slow rate of quasi-static tests, the deformation mechanisms can be easily examined and capture of each phase.

Hull [14] reported that two of five significant parameters affecting specific energy absorption is shape and dimensions. Farley [15] studied the influence of geometrical dimensions on energy dissipation of tubular composite structure. Stated that the change in inside diameter of the wall thickness ratio can lead to a rise in absorbing energy value. Ross et al. [16] investigated experimentally on buckling for six domes of Hemi-ellipsoidal tubes under external axial pressure and concluded that raising the aspect ratio of the hemi-ellipsoidal dome between (0.25 - 0.7) lead to increase the buckling pressure between (420 - 931). Mahdi et al. [17][18] studied experimentally the effect of the vertex angle of cone-cone and cone-cylindrical-cone specimens on crashworthiness parameters and energy absorption under axial compression load. They demonstrated that tube with a vertex angle 20^0 and 25^0 was more effective than other angles used experimentally.

In many studies [12][19][20] have been used circular and square cross sections to determine the crashworthiness parameters and energy absorption of the composite materials. Thornton et al. [21] concluded that the design of a circular composite tube is more efficient than both square and a rectangular cross-section of a composite structure. Furthermore, this result is consistent with studies by Mamalis et al. [22][23] . Jimenez et al. [24] conducted an investigation on ‘‘I” cross-section tubes. The study demonstrated that the square section profile of composite tube absorbed 15% more energy than ‘‘I” section composite tubes. It appears from the aforementioned investigations that all authors in this field are in agreement that geometric shape is an extreme parameter that affected the absorption of energy. However, a few searches have been implemented on the special geometry of the composite tubular structure. Palanivelu et al.[25] studied geometrical shape effect of composite material on the crushing mode and energy absorber under quasi-static test, and concluded that special geometric shapes such as hourglass, and conical-circular are more preferable to the standard geometric shapes as a square and hexagonal tube in terms of crushing properties and absorption of energy. Abdewi et al. [26] studied effect two kinds of tubes, a radial corrugated tubular composite and a circular tubular composite of woven glass/epoxy laminated composite on the energy absorption. The result shows that the circular composite tube absorbs less energy than the tubular radial corrugated composite.

A search of the literature has revealed no study of the effect (RCCS) of natural composite, especially with jute/epoxy materials as energy absorption capabilities. That was the main motivation behind this study. Hence, this search will help to provide more information to the prior contributions to crashworthiness knowledge. Circular composite specimen (CCS) was manufactured and tested in the same conditions to ensure a fair comparison between both two geometric shapes.

Previous studies[1][2] have demonstrated the fiber orientation along with the axial direction of the tube structure is capable to absorb more energy than other fiber orientations. Therefore, the uni-directional fibre configuration with the above-mentioned factors has been chosen for this work. In order to yield a considerable deceleration during a crash, the failure of tubes should exhibit bending, delamination,

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fibre fracture, friction, and axial cracking modes [3]. To obtain the above-mentioned failure manner and to decrease the initial maximum crush force as much as possible, a triggering mechanism is extremely important for the progressive and stable failure[4]. Hence, the tulip triggering mechanism can be considered as a favorable design compared to other trigger mechanisms[5]. Thus, depending on the above-mentioned facts, TT mechanism would be more applicable in the current study. However, the purpose of the present research is to study the effects of different geometrical shapes on crashworthiness characteristic of natural jute fibre/epoxy composite tubes. The test parameters such as the total energy absorption, specific energy absorption, crushing mechanism, failure mode, and crush load efficiency are presented in detail:

2. Methodology:

2.1. Geometry and Materials Selection:

Two types of tubes, namely are (CCS) and (RCCS), were fabricated in the same conditions made of three layers. (Please note Figure 1 for the utilized method). Details on dimensions are shown below in Table 1. The jute fibers (in mat form of 350 gsm with orientation 0^0 and 90^0) is selected as reinforcement and Epoxy material as matrix. Epoxy resin (Auto-Fix 1710-A) and Hardener (Auto-Fix 1345-B) are supplied by Chemibond Enterprise SDN-EHD, Malaysia.

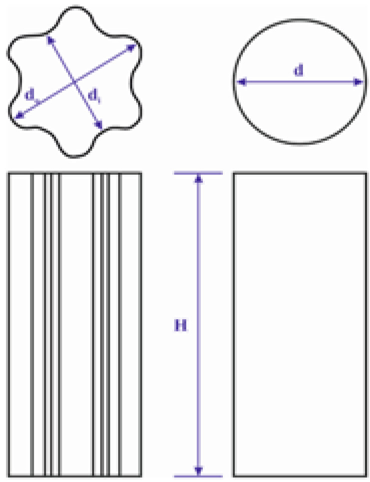

Figure 1. Schema for samples

Table 1. Description of natural jute /epoxy composite specimen.

Type of specimen	N	H,mm	d_O,mm	di,mm	D,mm	Number of pattern tested
CCS	3	100	-	-	50	3
RCCS	3	100	50	38	-	3

2.2. Fabrication and sampling process:

In this experiment, the principle of combination of simple manual layup with compression bladder molding method were used. Both types of hollow molds were made by CNC at the workshop from aluminum alloy with 15 cm height and the diameters for each one are shown in Table 1(Please noted Figure. 1 for the process utilized). First, a wax/release was applied to the mold's surface to prevent the epoxy from sticking to the mold surface. The jute mat was trimmed to the appropriate size of the mold, then weighed in order to use the equivalent epoxy of three layers. Epoxy and hardener were mixed by an electric mixer at ratio (1:1) as per the supplier's instructions. Electric mixer was used in order to prevent air bubble formation in a mixture. The epoxy resin was poured and spread by using a brush onto the jute layers and then wrapping of the fiber around the mandrel. A steel roller was moved over each jute- epoxy layer under a mild press down to dispose of air trapped from the laminate and to obtain the required thickness.

Then peel/release ply, release film, and bleeder film were cut as per the mold size and placed at the surface of layers before bagging film was draped over entire part and constant vacuum pressure of 6 bars applied (refer to Figure 2).The fabricated specimens were left to cure for 24 h at room temperature ((27^{0}c±2%). After that, the specimens were extracted from the rubber bladder and mold. The post-curing was conducted in on oven for 8 h at 60^{0}c and 4 h at 100^{0}c.The fabricated tubes process were repeated three times. Finally, all tubes were cut into the required specimen size with a height of (100 mm) by using bench saw; a tulip trigger was done by using an angle grinder for each one. Finally, the cured specimens were extricated from the mandrels and made ready for the test as shown in Figure 3.

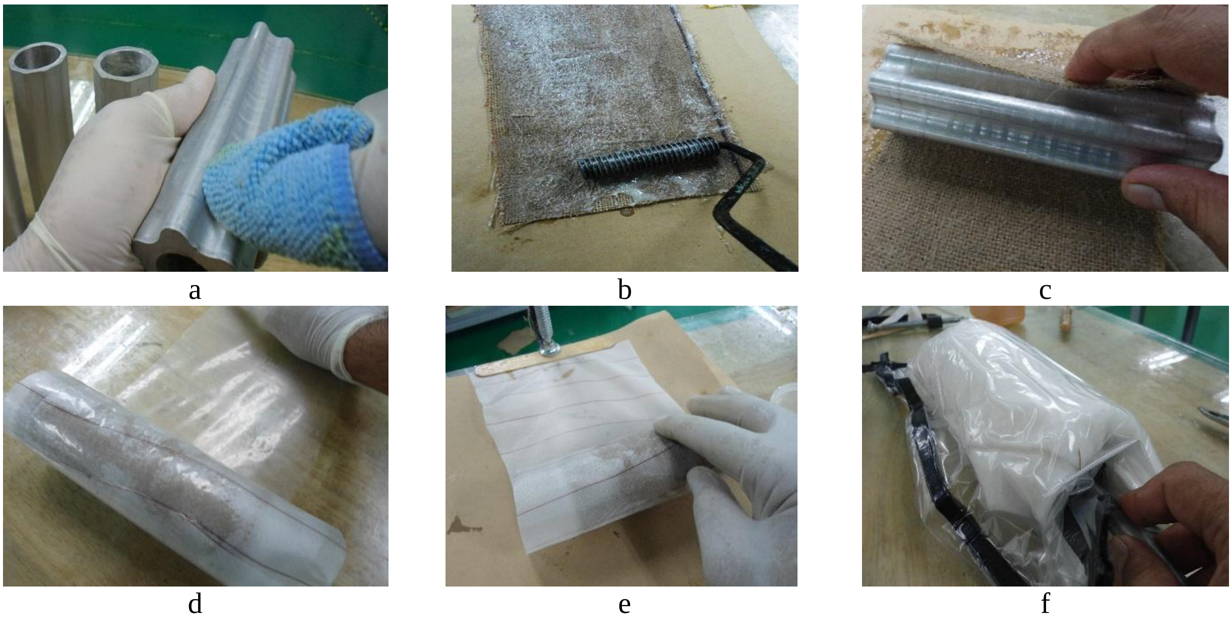

Figure 2. Fabrication process of jute/epoxy composite specimen: a. Apply wax ; b. Apply epoxy ; c. wrapping material ; d. Peel/release ply; e. Release film; and f. Apply vacuum pressure.

2.3. Experimental Testing Procedure:

All the tests were done under the same conditions for both types of tubular specimens. Testing of the specimens was performed by applying-uniaxial quasi-static compression forces using an Autograph AG-X. In addition, Shimadzu Universal Testing Machine with a 100 kN loading capacity was used, UTEM, Melaka, Malaysia. The testing was conducted based on ASTM: D7336M-16 with stroke set to 90 mm. The crosshead speed was at rate 10 mm/min. Each specimen was positioned on the lower fixed platen and were crushed axially by the parallel platen. Three replicate tests were done for each sample with three layers. Load and displacement test data were obtained by the automatic acquisition system to determine the crashworthiness parameters and the energy absorbance of the designed specimens.

3. Results and discussion:

The typical force–displacement graph can be distributed into three outstanding regions as in Figure (4). The first region I represents pre-crushing phase, in which the load (P) increases dramatically and reaches an initial maximum load P_{max} within elastic failure behavior before dropping. In the second region (II), the load fluctuated about a mean load over the crushing process in the plastic failure region and its associated the post-crushing phase. The force-displacement graph exhibited the P_{max} ,$\bar{P}$ and the displacement of the final failure. In the third region (III), known as the compaction phase, the load increases drastically and non-linearly because of debris accumulations at the end of the tube. This region was not taken into account due to its small absorb energy compare with post-crushing region. The test result was detailed in the next section. Crush phases and force-displacement graph of RCCS and CCS were compared in Figures (5) and (6), respectively.

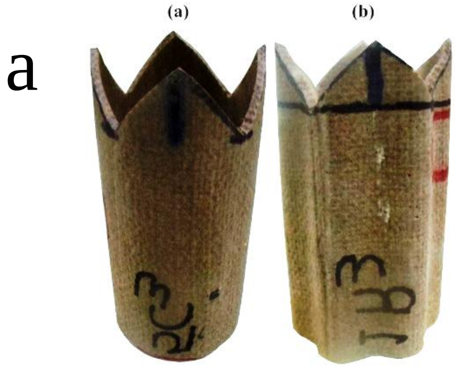

Figure 3. Photograph: - a. CCS; and b. RCCS.

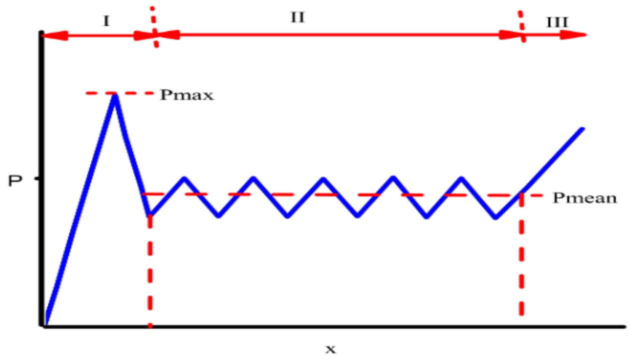

Figure 4. Force-displacement graph response.

3.1. Failure mechanisms:

3.1.1. Failure mechanism of RCCT:

Figure 5 shows deformation photographs taken during various crushing stages of corrugated configuration with demonstrates load-displacement graph in the test. It is clear that all RCCS specimens demonstrated a stable and gradually collapse from the top end by splaying and brittle fracture modes. From Figure 5b, it can be seen that the axial compression load escalated initially at pre-crushing zone. The first peak load attains a maximum valueP_{max} . (9.21KN) at the displacement of 19mm and then after a small displacement, the fluctuating began around the mean crush load in the second stage, which is called the post-crushing stage, due to lamina bending and sequence of micro-cracking processes characterizing each case of deformation. The maximum load magnitude in this post-crushing zone was 11 kN at the displacement of 56.1 mm. High energy absorption means having a large crushing area and hence a higher potential to absorb energy by frictional impacts and delamination at the platen/tube specimen interface (please see Figure 6). The load–crush distance of lamina bending crushing manner exhibited a majority of serrations with small capacity. This condition causes to grow the required stresses to initiate crack propagation and consequently higher energy absorption. In lamina bending and brittle fracture, a large amount of intralaminar and interlaminar cracks were created in the crush region. Thereafter, the compaction zone occurred at the last stage, wherein the load rises drastically due to debris accumulations and material densification of the tube has been completely compressed. RCCT displayed significant buckling resistance during quasi-static test. Minimal fluctuating load along RCCT crushing length was also noted. As a result, the main energy absorption was mostly contributed from lamina bending, axial cracks, continuous fiber delamination, and friction.

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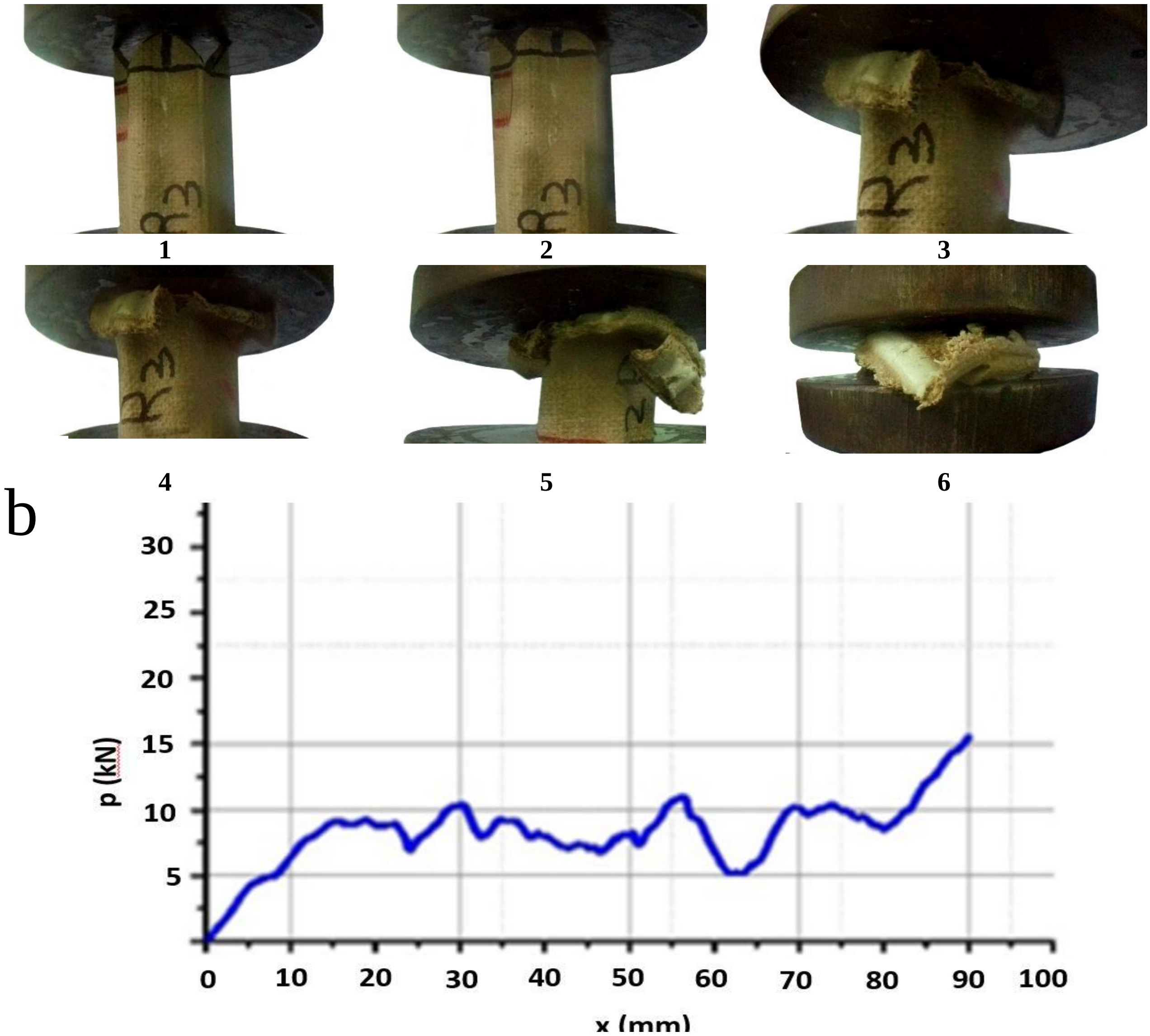

Figure. 5. Specimen under the quasi-static test of RCCS (a) photographs of different crushing phases (b) force vs displacement

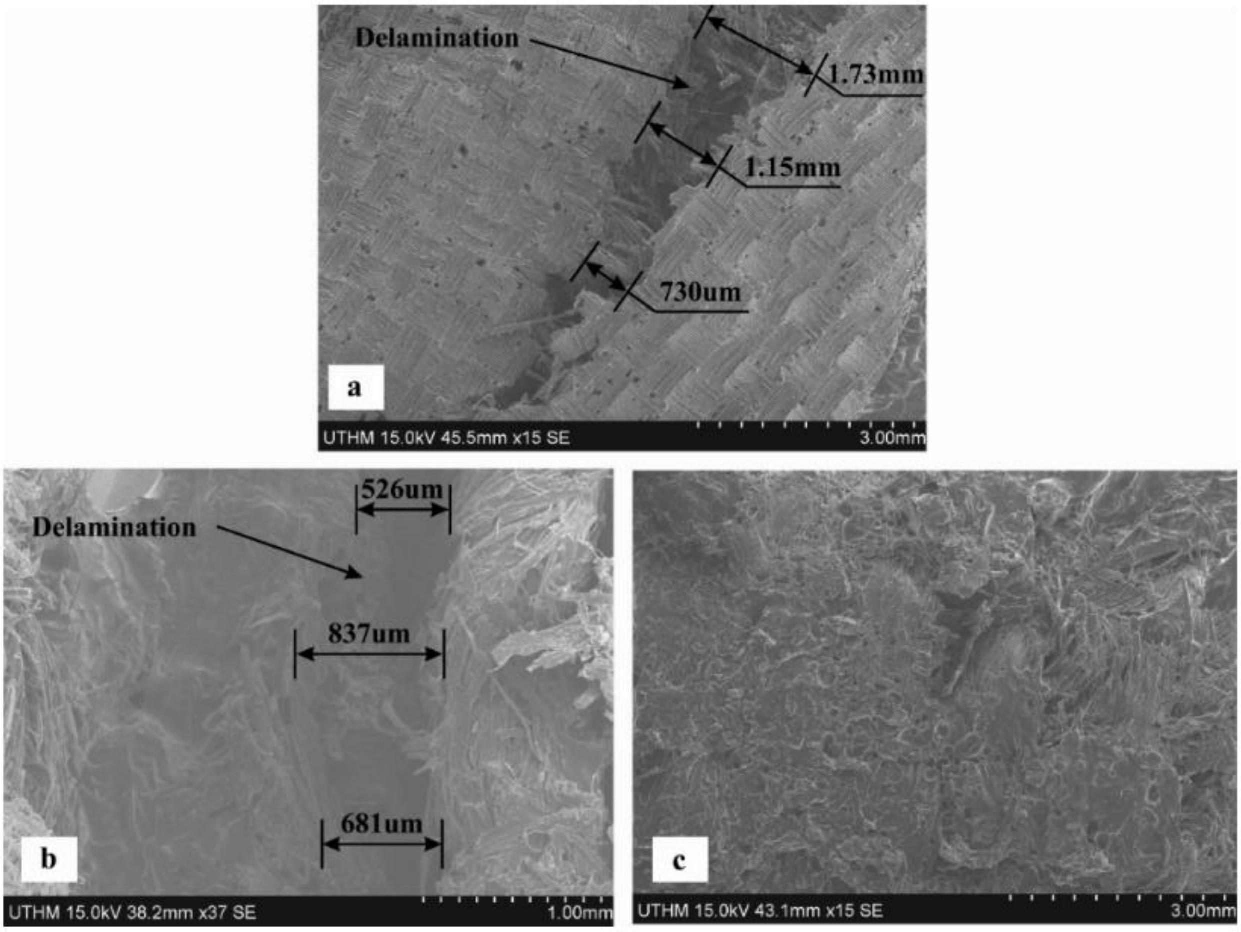

Figure 6. Scanning electron microscopy specimens of RCCT showing (a) axial crack (b) delamination (c) friction affect

3.1.2. Failure mechanism of CCS:

As indicated in Figure 7, CCS has almost comparable failure mechanism of RCCS. Nevertheless, CCS patterns record lower maximum peak force than the RCCT patterns. Failure starts at the first peak force of 8.34 kN at 23.35 mm, which corresponds to end crushing trigger at the pre-crushing stage. Then the force value slightly dropped before it starts to oscillate around the average crush force, which is indicative of lamina bending or splaying mode in the crushing region. This was also because of the sequence of various micro-cracking processes with delamination that were formed in the crush front region of specimen for each case of collapse. The second peak load magnitude in this post-crushing zone was 9.49 KN at 34.09 mm. the major cracks began of long axial and lamina bending was also formed along the tube. However, at 75.01 mm displacement the load declined, which occurred at the final crushing in the second stage. This was because of the load resistance reduction of the remained part of the tested tube. In the third stage of compaction region, the load increased rapidly due to the debris accumulation of specimen. As a result, the main energy dissipated was contributed from lamina bending, friction effect, axial cracks with delamination.

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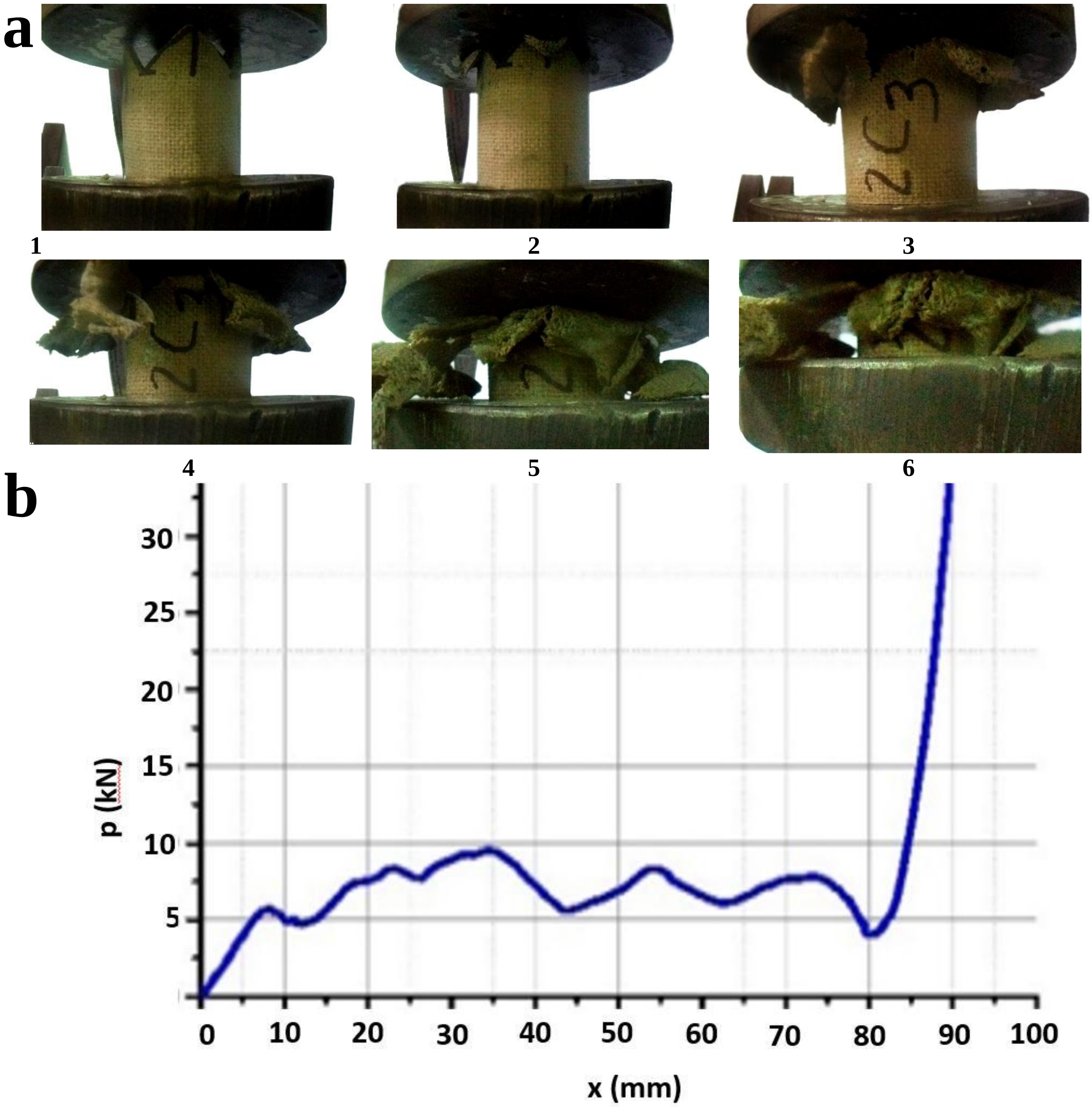

Figure.7. Specimen under the quasi-static test of CCS (a) photographs of different crushing phases (b) force vs displacement

3.2. Crashworthiness criteria:

Capability of crashworthiness can be evaluated by knowledge of various parameters, which illustrated in the next sections in details to judge the crushing performance:

3.2.1. Energy absorption (EA):

It is defined as the rate of energy dissipation during the crushing event of elements, which is represented by the plot underneath the graph of a load-displacement and calculated as:

$$EA = \int_0^x P\,dx \qquad (1)$$

Where P is an instantaneous crushing force and x is crushing displacement. In this test, since the compaction region often started after 80mm displacement. Therefore, overall energy absorption was calculated until 80mm of crushing displacement, which equals only 80% of the deformation. This was done to facilitate verification.

3.2.2. Crush efficiency (CE):

It is a key parameter to assess the performance of EA and evaluate the stability of the crushing process. The CE is determined as the function of the ratio between average force and maximum peak force. Thus, a high magnitude of CE, which approaches unity for significant energy absorption, indicates that sustainable crush force is close to maximum peak force. It can be computed as:

$$CE = \frac{Pmean}{Pmax} \qquad (2)$$

Table 2.Average Crashworthiness parameters of radial corrugated and circle composite specimens.

Tube type	Crashed mass,g	P_{max} ,KN	$\bar{P}$, KN	EA ,J	SEA,J/g	CE%
RCCS	28.4	10.95	8.82	625.64	22	81%
CCS	31.4	9.07	6.9	505.22	16.1	76%

3.2.3. Specific energy absorption (SEA):

It is considered an essential parameter to compare the energy absorption capacity with the different materials, which is measured as the amount of total energy absorbed per unit mass of crushed material. In general, the high SEA, the more effective the energy absorber. Therefore, the large value of SEA is indicative of the lightweight absorber. Table (2) indicates that different structure geometry leads to significant increment in specific absorption.

4. Optimized design and comparison with other crashworthiness parameters:

From the test results in Table 2 it can be observed that the natural jute/epoxy tube with radial corrugated tube has a larger SEA of 22 kJ/Kg and the CFE is 81%. As shown in Figure 5, it is noted that RCCS configuration exhibit more stability from the top point up to end under quasi-static test than CCS tube, which dropped slightly before the end of crushing test. Furthermore, the radial corrugated specimens are less likely to buckle comparing to circle composite tube. P.J. Cunat [6] studied the crashworthiness energy absorption of stainless steel and stated the rate of SAE for the steel tubes were 12.5 to 38 J/g. J. Bouchet [7] stated the SAE of the aluminum tube ranged from 22 to 43 J/g. Each stainless steel and aluminum structure had CFE less than 60%. Therefore, it is concluded that optimized jute/epoxy composite tube has outperformed the metal crashworthiness performance. E. F. Abdewi [8] and H. S. Sultan et al. [9] reported the SAE of glass/epoxy composite structure were 12.2 and 15.3 KJ/Kg, respectively. Elgalai et al.

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[10] studied two types of composite material, namely, carbon fiber/epoxy and glass fiber/epoxy with different corrugation angles, and reported the SEA ranged from (13.33 to 15.70) kJ/kg and (6.75 to 9.53)kJ/kg, respectively. Furthermore, as displayed in Figures (5a) brittle fracture with a progressive along the crushing process is identical to principal energy absorption of the tubular synthetic Fiber-reinforced composites. Therefore, it is noted that natural jute/epoxy composite material can be a premium candidate compared to synthetic fibers in most engineering application.

To date, investigations on crashworthiness capabilities by using natural composite tube is still insufficient. Oshkovr et al. [11] and S. A. Oshkovr et al. [12] investigated the crashworthiness capability of natural silk/epoxy tubes and stated the SAE for specimens were ranged between (4.2 - 13.4) J/g and the CFE ranged between (0.38 - 0.45). In relation to failure manner, A.Eshkoor et al.[11] reported in their work that generally buckling that occurred, either local or at mid-length of tubes, are the two major characteristics of natural silk/epoxy tubes. S. A. Oshkovr et al. [12] reported that their specimens with 24 and 30 laminates in different lengths (50, 80 and 120)mm showed mid-length buckling, which was failed starting at the mid of the specimen length which then progressed to overall buckling followed by catastrophic failure mode. As observed from prior studies, unlike the catastrophic failure of silk/epoxy specimen, the jute/epoxy composite specimens were crushed in a brittle mode with a progressive crushing pattern. . Thus, the natural jute/epoxy tube outperformed the tubular silk/epoxy composite structure in terms of energy absorption capability.

5. Conclusion:

In this work, the effect of geometric shapes on the deformation manner and the corresponding energy dissipation of natural composite samples have been carefully studied. Two different structures shape (namely circular and corrugated) were manufactured and tested in the same conditions to provide the appropriate environment for comparison. The two kinds of samples were undergone to axial quasi-static loading at speed 10mm/min. Depending on the experimental results the following can be inferred:

The geometrical shapes affect the quasi-static deformation mechanism of woven jute fibers/epoxy composite samples.

The corrugated and circular cross-sectional samples with three layers exhibited stable and progressive deformation failure mechanisms. The failure modes associated with these samples were lamina bending, friction effect, axial cracks with delamination.

The corrugated configuration tube can be considered as the most favorable compared to the circular configuration tube, which showed the higher of SEA and CE value of 22J/g and 81% respectively. Thus, the jute/epoxy composite tube is possible to be utilized as an energy absorption device.

Nomenclature:

d	:	inner diameter of the circular specimen
d_O	:	outer diameter of the corrugated specimen
d_i	:	inner diameter of the corrugated specimen
EA	:	energy absorption
EAS	:	specific absorbed energy
CE	:	crush efficiency

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H	:	height of specimen
N	:	number of plies
P_{max}	:	maximum force
$\bar{P}$	:	average force
RCCS	:	composite specimen of radial corrugated shape
x	:	crush length

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