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On The Energy Absorption of Natural Woven Silk/Epoxy Composite Tube

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Abstract

In this study the energy absorption response and load carrying capability of *Bombyx mori* (*B. mori*) natural silk fibre/Epoxy composite cylindrical tubes under an axial quasi-static compression was investigated. The composite tubes were prepared using mandrel assisted hand lay-up technique. The tube was fabricated using 24 layers of *B. mori* natural silk fibre, fully wetted with epoxy matrix. The tube was then cut into varied lengths of 50 mm, 80 mm, and 120 mm, respectively. Three specimens were tested in each category. The experimental results were analysed by measuring maximum peak load (P_{max}), specific absorbed energy (SAE), and total energy absorption (TE) as a function of tube length. Findings show results being varied according to tube length in unpredictable manners. Failure fragmentation of the tubes was analysed from photographs obtained during the test using high resolution camera, which showed micro cracks induced by compression load as the predominant source of failure.

Keywords: Woven Natural silk fibre; laminated composite; Energy absorption

Introduction

Presently, it has become fashionable to use composite materials for crashworthiness and energy attenuation component parts in transportation industries because of its ability to be tailored according to the designer's choice. Engineering materials researchers all over the globe are now tasked with the challenge of developing superior and supper superior composite structures for the manufacturing industries. The whole concept of crashworthiness is the ability of a structure to protect its occupants during a survivable impact with external objects. This fact remains the most important criterion in designing structures used in the transportation industries today [1-3]. Structures are then investigated for crashworthiness to ascertain their worthiness and predict their load carrying capabilities to avoid the occurrence of catastrophic failure during impact.

Other benefits associated with fibre-reinforced plastic (FRP) which made it become the trendy in transportation industries are durability, strength to weight ratio and low fuel consumption due to reduced weight. These advantages have intensified the use of FRP composites in the improvement of vehicle structural crashworthiness by their application in specific automobile parts as collapsible energy attenuators during crash [3-6]. Its progressive deformation manner and stable collapse features which are displayed by some FRP are the preferred qualities of any automobile structure, as they reduce the impact force experienced by the passengers during sudden collision. Previous studies show that crashworthiness parameters for various thin-walled tubes made from a range of composite materials in diverse geometries have been investigated [1,3-5,7-14]. Failure analysis of some FRP composites structures under axial compression load which were compared, show that most composites do not collapse plastically as metals do, but collapse at various unpredictable modes in brittle manners with micro-cracks as the predominant failure mechanism. It was indicated in the reviewed literatures that these failure modes depend on the shape of the specimen, material characteristics of the composite structures and the testing parameters. This behaviour of some composite structures has posed a threat and researchers are in constant search of solutions to this threat. In line with the above statement, we present our work on *Bombyx mori* natural woven fibre/epoxy composite. This present work tends to investigate the deformation characteristics of *Bombyx mori* composite fibre reinforced plastic (FRP) cylindrical tubes as a function of varied length. The contributions of this study will add value to the scientific data relating to FRP thin-wall collapsible energy absorbers and natural silk fibre respectively.

Materials and Method

The materials used for the fabrication of the composite tubes were *Bombyx mori* (*B. mori*) woven natural silk fibre and Epoxy matrix mixed with epoxy hardener. The cylindrical composite tubes, consist of 24 layers of *B. mori* woven natural silk fabric and epoxy resin as matrix was fabricated using mandrel assisted hand lay-up method [3,8]. The tube which was cut into varied lengths of 50 mm, 80 mm and 120 mm were then subjected to axial quasi-static compression test. Three samples were used for each category. The testing equipment was a fully automated INSTRON MTS 810 universal testing machine with 250 KN loading capacity. All tests were performed at a constant test crosshead speed of 20 mm/min. The testing work were performed without any special conditioning of the test specimens, since the ambient conditions in the laboratory room at the time of test were within the range of the recommended control conditions for testing of composite materials. The temperature was within 23 ± 3 and the relative humidity was within 50-60%. Two flat plates as fixtures mounted opposite to each other were used to accomplish the test. Finally, the quasi-static compression test results captured via the software were extracted and analysed.

Quasi static experimental test

The load-carrying capability of materials under quasi static experimental crushing test can be studied via two load levels, the

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initial crushing load and average crushing load. The initial crushing load can be obtained directly from the load-displacement reaction, while the average crushing load can be obtained by averaging the crush load values over the crush displacements through the post-crush zone. Figure 1 shows a schematic representation of load-displacement curve of a composite material specimen tested for load carrying capability under quasi axial static experiment. There were three vital zones explained; the first was the pre-crushing zone which indicates the pre-crushing behaviour of the composite specimen, this zone terminates once there is initiation of failure in the specimen. The second zone is known as the post-crushing zone, this is the picture of failure spreads across the whole specimen and characterized by average crushing load. The third zone is known as the compaction zone, it illustrate the behaviour of specimen in compaction, causing sharp increase in the load curve until final failure occurs. The load-displacement curves are also useful to deduce crashworthiness parameters, used in comparing load-carrying and energy absorption capacities of different composite materials and structures. The diagram assists researcher to analyse the crashworthiness characteristics of composites structures with important parameters such as:

• Absorbed crash energy E: referred to the area under the load-displacement curve

• Maximum load (P_{max}): referred as the first peak load value

• Maximum compressive strength, σ_{max}: referred as the peak load, P_{max} to cylindrical tube cross sectional area A.

• The post-crushing displacement, δ: referred to the total displacement of crushed specimen in load-displacement curve.

• Specific absorbed energy (SAE): referred to the absorbed crash energy per unit of the crushed specimen mass.

• Average crushing load, $\bar{\boldsymbol{P}}$ obtained from the following equation:

$$\bar{P} = \frac{1}{\delta}\int_0^{\delta} p d\delta$$

Where, the load and the post-crush displacement are defined as δ and P, respectively.

• Stroke efficiency (SE): referred to the post-crush displacement, δ of the specimen's total length L.

• Crash force efficiency, (CFE): referred to the ratio of the average crushing load, $\bar{\boldsymbol{P}}$ to the peak load, P_{max}.

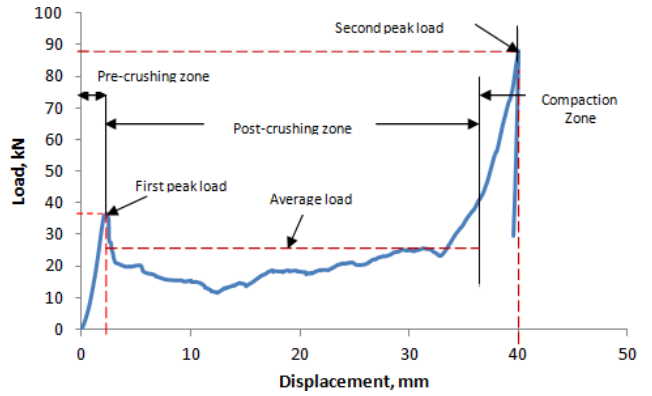

Figure 1: Schematic diagram of load versus displacement curve, showing pre-crushing, post-crushing and compaction zones.

Results and Discussion

In the Figures 2a-4a shown below, it represents the photographs of 24 layered *B. mori*/Epoxy composite tubes with lengths of 50 mm, 80 mm and 120 mm, obtained at different stages of the test and Figures 2b-4b show the load-displacement deformation curve credited to each composite tube during the test. Load-displacement curves are mainly used to interpret the amount of load any structure can carry and at what displacement. As observed from the test curve, there were two peak loads, the first peak which occurred within the pre-crushing zone, behaved lineally until it reached the peak, sharp drops indicating failure initiations were immediately observed. This marks the end of elastic behaviour and ushers in the post crushing behaviour zone as indicated in Figure 1. At the post-crushing zone, the curves continued with an oscillation of the loads around an average value lower than the first peak load until compaction zones were reached. At the compacting zone, the compressive load continued to exert force on the already deformed walls of the composite tubes and initiating a second peak that is higher than the first. The last stage observed were the sharp vertical downward drops of the curve, which signifies total collapse of the composite structure.

Failure modes

The failure behaviours observed suggests that length of tubes can affect their crashworthiness and absorbed energy properties as each length failed in a different manner. Generally, the 24 layer *B. mori*/epoxy composite tubes under axial compression load presents a ductile deformation without debris splitting as its being crushed. Observations of 50 mm tube length specimen, Figure 2a show that cracks were initiated at the contact surfaces of the tubes with the metal plates and progressed in a crushing progressive manner in opposite directions, leading to a twist failure mid of the tube before complete collapse occurred. The manner of failure mode found in this experiment,

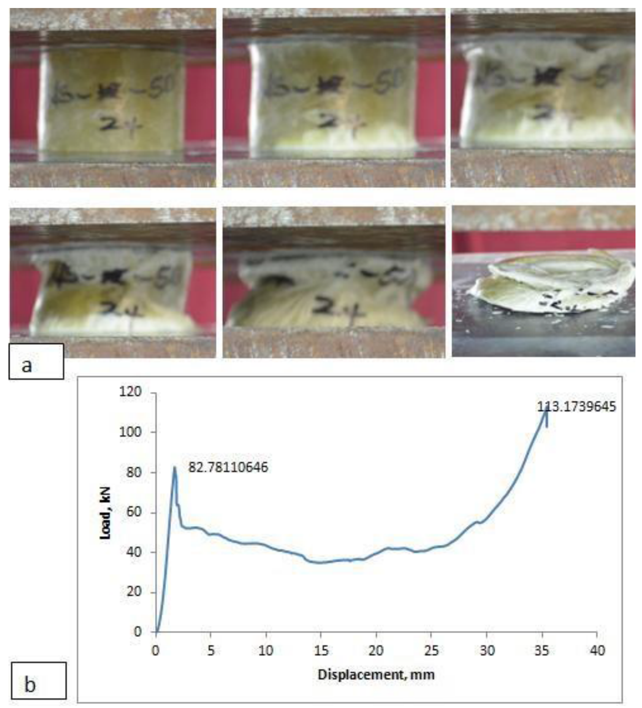

Figure 2: Axial compression test of B.mori/epoxy composite cylindrical tube with 50 mm length (a) Photographs of samples during test (b) Load versus displacement curve.

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partially agreed [2,15] of a square tube under axial compressive load. On like these square tubes and even the one we previously observed in our experiments [1,8,16], which experienced mid-way buckling failures and splitting at the corners, there was no buckling nor corner splitting observed with the present 24 layer *B. mori*/Epoxy composite tube, 50 mm length. In brittle composite materials such as carbon fibre or glass fibre epoxy resin reinforced composite structures, their crushing behaviour were cyclic behaviour of interlaminar cracks spreading in the midst of layers in the crushing zone of the tube and forming lamina bundles as the crush, the current experiment did not behave in like manner. The load/displacement curve Figure 2b, indicated 82.78 kN as the first peak load and 113.17 kN as the second peak [15].

In Figures 3a which showed the experimental photos of 80 mm composite tube length, the tube was characterized by unstable mid-length circumferential crack which propagated, leading to the encapsulation of the top half into the bottom half of the cylindrical composite tube. The tube wall of the bottom half fractured vertically owing to the force induced by the encapsulated half of the tube. In Figure 3b the load/displacement curve showed 76.57kN as the first peak and 116.64 kN as the second peak. These values indicated slight decrease in the first peak from the previous 50 mm tube length in Figure 2b and increase in the second peak.

Figure 4a show the experimental photos of 120 mm tube length specimen, observation indicated that cracks started at the contact surfaces of the tubes with the metal plates and progressed in a crushing progressive manner from both the top and bottom sides of the tube. The failure mode observed agrees partially with Mamalis mode I and II failure mode classification [15]. It is worthy to note also the non-existence of buckling effects in 120 mm tube length as the tube progressively crushed down. However, the progressive crushing behaviour continued until total failure was accomplished, traces of laminate delamination were also evidence. The load-displacement curve in Figure 4b show that first peak was reached at 70.5 kN and the second was at 111.8 kN respectively. These values showed further decrease in first peak load when compared with the value obtained from 50 mm tube length. The inconsistency of the elastic limit therefore could be as a result of human errors during fabrication of the samples or unpredictable nature of FRP composites.

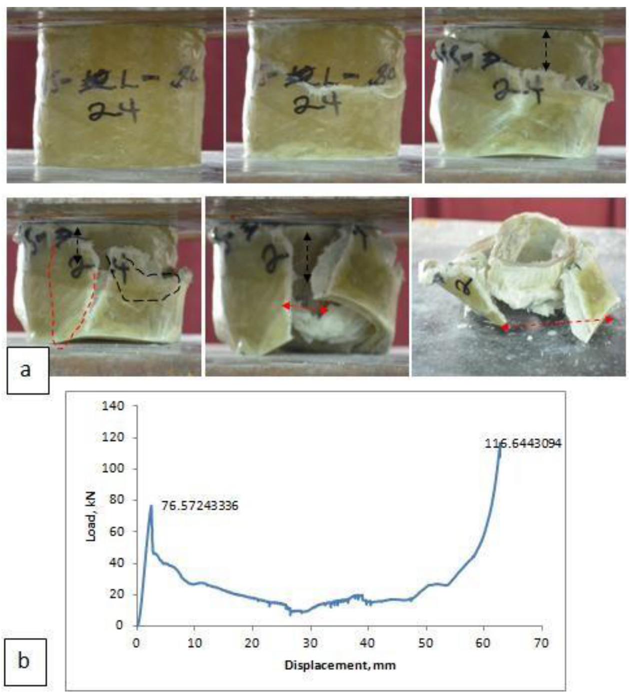

Figure 3: Axial compression test of B.mori/epoxy composite cylindrical tube with 80 mm length (a) Photographs of samples during test (b) Load versus displacement curve.

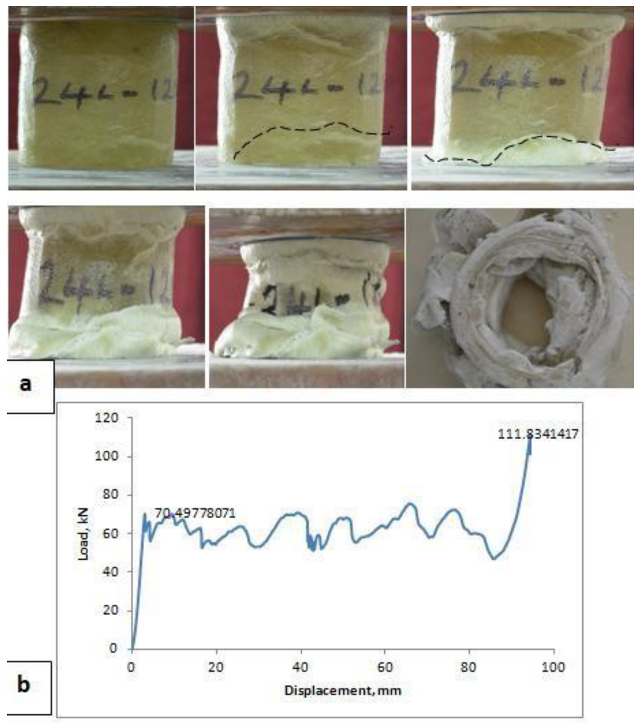

Figure 4: Axial compression test of B.mori composite cylindrical tube with 120 mm length (a) Photographs of samples during test (b) Load versus displacement curve.

Crashworthiness characteristics

The Figure 5 through to Figure 8 shown below presents the behaviour of crushing load and the energy absorption of the *B. mori* fibre/epoxy composite tubes. Parameters analysed and discussed in this section were maximum compressive peak load (P_{max}), average compressive load ($\bar{P}$), total absorbed energy (E_{total}), specific absorption energy (SAE) and crushing force efficiency (CFE).

Peak load

The load-displacement curve reveals the crushing history of each tube in relation to the length of the tubes. Crushing of the specimen begins after a critical load value known as Peak Load is reached. Peak load is defined as the maximum load a structure can carry before initiation of failure occurs. In Figure 5, observation show that the 50 mm tube length performed better than the other two lengths when compared. The value of peak load decreased as tube length increased. The percentage ratio of increase was inconsistent between the varied lengths of the composite tube. Under this investigation two peak loads were observed, classified as first and second peak loads. The most important is the first peak which occurs just before the initiation of failure. Once there is the formation of any micro crack in the tube structure, it soon propagates into macro fracture and leading to a progressive crushing failure as in the case of *B. mori*/epoxy tubes. The

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values of the first peak load seen as the most important peak load values were plotted below. The result share similarity with reported findings in which it was also reported that peak load decreased with increase in length of a thin wall composite tube reinforcement [2,15,16]. These reports also alleged tube geometry and composite material properties as critical in influencing the peak load value, while average load value are influenced by available modes of failures.

Specific absorbed energy

The diagram in Figure 6, show the behaviour of 24 layer composite tube in terms of specific absorbed energy. Specific absorbed energy is defined as the absorbed energy per unit mass of a particular material. This material property is very useful in engineering material analysis; it is used to ascertain the best energy absorbing material per unit mass, during material selection for energy attenuation related applications. In this experiment, result showed an increase in value of the absorbed energy as the tube length increased. Though, between 50 mm and 80 mm tube lengths on this experiment, there was no significant increase noticed. A comparable observation was reported to imply that there is no mono behaviour of composite tubes in terms of their specific energy absorption characteristics [16].

Total energy absorption

Figure 7 displayed the behaviour of the total energy absorption, this material quantity is defined as the total energy absorbed by the specimen at complete failure of the structure. FRP composites use their deformation patterns to absorb energy as they deform, meaning that the pattern of deformation is also very important so that more energy could be absorbed, it has also been reported that more energy were absorbed during deformation than before deformation. The deformation mechanism and the shape of the structures are both important factors that can influence total energy absorption property. The value of total energy absorption could be estimated as being equal to the area under the load-displacement curve (Figure 7).

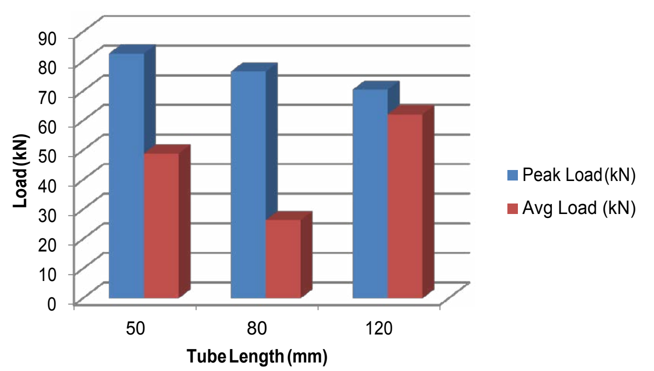

Figure 5: Peak and Average load characteristics of composite tubes.

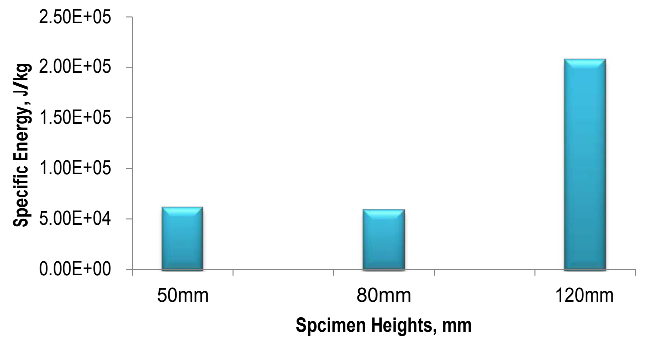

Figure 6: Specific energy, (SAE) for B.mori/epoxy composite cylindrical tubes.

Figure 8 show case the behaviour of the Crush Force Efficiency (CFE) of the 24 layers composite tube in this experiment. This property is another important factor to determine the crashworthiness of any material. It is defined as the average load value per peak load value of a structure and ranging from 0.0 to 1.0. Failure modes of structures can be predicted by using these values; progressive deformed structure has bigger values, while brittle structure has smaller values. In this study of 24 layers *B. mori*/epoxy composite tubes, the crush force efficiency (CFE) increased with increasing length of the cylindrical tubes. The ratios of increase to the tube lengths were not proportional though, the percentage (%) of increase was compared. It was clear from the bar chart that the change between 50 mm and 80 mm tube lengths were negligible (Figure 8).

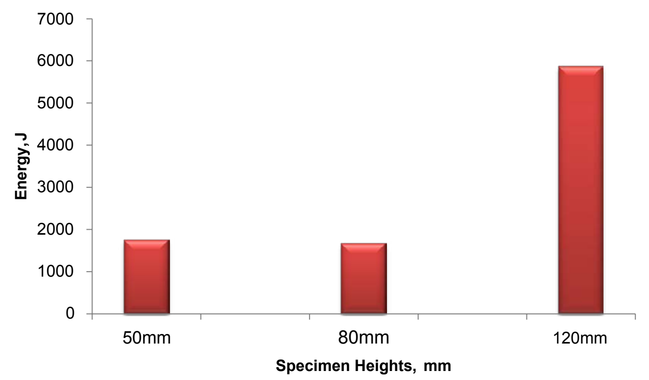

Figure 7: Total absorbed crash energy, (TAE) of B.mori/epoxy cylindrical composite tubes.

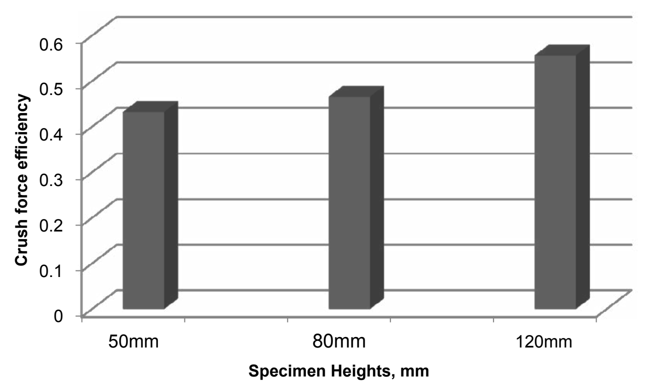

Figure 8: Crush force efficiency (CFE) characteristics for B.mori/epoxy composite cylindrical tubes.

Conclusions

The study to understand the effect of length to crush behaviour of 24 layered composite cylindrical tubes has been investigated. This is another attempt to understand and analyse mode of failure, load carrying capabilities and the crashworthiness, specifically for a 24 layered *B. mori* fibres/epoxy composite cylindrical tube, cut at varied lengths of 50 mm, 80 mm and 120 mm. *B. mori* composite structures must be investigated thoroughly and well understood before its application in critical areas could be accepted in the manufacturing industries for energy absorption, crash or impact/collision design applications. It is on this note that we summarize our findings. Generally, this investigation has established the fact that tube lengths can influence the crash energy absorption. Among the tubes tested, 50 mm tube length outperformed 80 mm and 120 mm by absorbing more load before failing. In energy absorption as well as crush force efficiency, the 120 mm tube length performed better than the others. Varied failure modes were observed, beginning with internal micro cracks at the contact surfaces and propagated through the whole tube, internal delamination of the laminates and fibre breakages which led to total collapse of the tube.

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