Energy absorption capability of date palm leaf fiber reinforced epoxy composites rectangular tubes

ARTICLE INFO

Keywords:
Date palm fiber
Bio-composite
Crashworthiness
Energy absorption

ABSTRACT

This paper introduces the date palm leaf fiber (DPLF) as a possible natural fiber candidate to the automotive applications. An extensive experimental program has been carried out to examine the energy absorption capability of rectangular tubes made of DPLF. The test rig has been designed to characterize different types of date palm leaf species. The species with the highest mechanical properties has been employed as a reinforcement to make the tested composite rectangular tubes. The wet wrapping manufacturing technique has been used to fabricate the composite structure. The fabricated tubes have been tested axially and laterally to examine the effect of loading directions into their crushing behavior and energy absorption capability. The crushed morphology, fracture surfaces, and sections through the specimen were studied by means of visual, optical microscopy and scanning electron microscopy (SEM). The results showed that the axially tested tubes have higher energy-absorption capability compared to the laterally crushed tubes.

1. Introduction

Over the last two decades, globalization has had a profound impact on how we view the world and its sustainability, particularly the production and disposal of manufactured goods. Today, interest in high strength plant fibers is soaring dramatically with global demand for less expensive/more partially biodegradable products. For example, the European Union has approved laws to reduce the use of synthetic materials. Thus, there has arisen drive to develop more-sustainable materials in the form of natural, biodegradable composites, or bio-composites, combining natural fibers and particles with a plant-based biodegradable polymer matrix [1–5]. Natural plant fibers have long been employed for engineering purposes, from papyrus as a soil retainer, to the incorporation of cotton fiber in foam insulation and wood fibers in phenolic clutch disks [6–8]. Such fibers are produced with less energy, are renewable resources, and are biodegradable at the end of their useful lives. They are light and provide excellent acoustic and thermal insulation. Some exhibit specific strength and/or specific modulus comparable to E-glass fibers (along with far higher energy absorption). Natural fibers are beginning to be used to reinforce conventional plastics (for example, Mercedes Benz door panels) [9–11]. Natural fibers have been mixed into concrete to improve its flexural properties [12]. Commonly they are used at short lengths and without optimal surface treatments to encourage bonding; they have rarely performed to their full potential. Bio-composites (natural fibers in plant-based or biodegradable matrixes) are actively being explored in various technical dimensions, due to their moisture resistance, low maintenance costs, durability, and ability to make use of naturally discarded natural materials [1,13–14], with an ever-increasing variety being described in the literature [9–10,15–24]. Most publications in this field have concentrated on the constituent types, volume fractions, and fiber treatment. The results generally show that increasing the fiber content increases composite strength and modulus up to a peak value, beyond which the properties deteriorate. A high fiber volume fraction can also improve moisture resistance and even biodegradability. In this paper, our focus is on date palm fiber (DPLF), which is strong, and widely available as an agricultural byproduct. The objective of this research paper is to investigate the effect of loading conditions on crushing behavior and energy absorption capability of date palm leaf fiber reinforced epoxy. Our ultimate aim is to carry out research that will allow DPLF to be used as reinforcement in an industrially useful partially biodegradable composite. A cost-effective DPLF-based partially biodegradable manufacturing material could be directly helpful in many areas composites rectangular tubes.

2. Experimental details

2.1. Materials

The materials used here can be divided into two types, the matrix materials, and fiber materials. The former consists of Epoxy resin Epolam 2015/2014 manufactured by Axon technologies (2015: resin, 2014: hardener). The components were used in the ratio 100 of resin to 32 of hardener by weight, according to the specification set by the manufacturer. The density of Epolam 2015 = 1.15 ± 0.1 g/cm³, Epolam 2014 = 0.96 ± 0.1 g/cm³, tensile strength of 70 MPa, flexural strength of 120, flexural modulus of 3.1 GPa, elongation at break of 5% and impact strength (Charpy) of 40 kJ/m², while the latter is the unidirectional long date palm leaf fiber (DPLF), which used as a filler material. Typical mechanical properties of DPLF are included here for comparison purposes. As cited for AL-Oqla, F.M. et al. [3], common date palm fibers would have the density of 0.9 to 1.2 g/cm³, an elongation of 2% to 19%, a tensile strength of 97 MPa to 196 MPa and Young’s modulus of 2.5 MPa to 5.4 MPa. The date palm leaf fiber morphology is shown in Fig. 1. Raw samples of the date palm leaves were removed from stems and preserved in polyethylene bags with date labels for identification. All samples were washed with tap water and manually dismantled into bundles of virgin fibers. The bundled fibers
were dried at room temperature before being separated in long fibers using a needle brush. The DPLF unidirectional fabric manufacturing process is shown in Fig. 2a. The composites prepared had a fiber-volume fraction of 31.4%. Peak force relationship with fiber content is shown in Fig. 2b. A rectangular mold was used to produce tubes of 10 cm long of DPLF/epoxy. The rectangular cross-section has been
Fig. 3. Schematic diagrams of mold (a) inner mandrel, (b) outer mold, (c) assemble.

Fig. 4. The fabrication process schematic diagrams for the rectangular tube. (1) Impregnate DPLF fabric wrap on the mandrel, (2) 24 Hours under compression, (3) Removal from the outer mold, (4) DPLF/epoxy tube removal from the mandrel.

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<tr>
<th>Table 1</th>
<th>Mechanical properties of date palm leaf fiber.</th>
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<tr>
<td>Modulus of Elasticity (GPa)</td>
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<tr>
<td>Poisson’s Ratio</td>
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<tr>
<td>Tensile strength (MPa)</td>
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<tr>
<td>Elongation at Break (%)</td>
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<td>Density (g/cm³)</td>
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<th>Table 2</th>
<th>Mechanical Properties of Epoxy resin (Epolam 2015/2014).</th>
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<tr>
<td>Young’s Modulus (GPa)</td>
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<tr>
<td>Poisson’s Ratio</td>
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<tr>
<td>Tensile strength (MPa)</td>
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<tr>
<td>Density (g/cm³)</td>
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employed to mitigate the brittle failure mechanism. This can only be assured by designing the mold with sharp corners, rather than round corners. Sharp corners initiate the rupture, which are definitely lead to fracture mechanism. The schematic diagrams of mold and mandrel are shown in Figs. 3 and 4. The mandrel was partitioned to facilitate the extraction process. As the mandrel introduces inside the mold under compression, it pulls the DPLF unidirectional fabric sheet wrapping the mandrel. The tubes were manufactured with 4 layers. The resulting wall thickness was 3 mm. After full curing, the wood mid-part of the aluminum mandrel was directly extracted; consequently, the upper and the lower parts were quickly removed. Mechanical properties of DPLF and the epoxy matrix are listed in Tables 1 and 2.

2.2. Testing procedures

2.2.1. Crushing tests

Quasi-static crushing tests were carried out to assess the crashworthiness and monitor the crushing mechanisms corresponding to each configuration. The tests were carried out using an Instron 8500 digital-testing machine with a full-scale load range of 250 kN. Steel plates were set parallel to each other prior to the initiation of the test. Three tests were conducted for each configuration for data reproducibility. The behavior of each arrangement under compression loading was recorded using a camera. The acquisition system of the universal testing machine recorded the load–displacement data at a constant speed.
crosshead speed of 5 mm/min. The test setup is shown in Fig. 5.

2.2.2. The well-known crashworthiness parameters

The parameters used to assess the crushing response are summarized in [4,5]. According to Mahdi and Hamouda [4], one of the most important aspects of evaluating crushing response is to keep the peak force (P) exerted on the protected occupants below the occupants’ tolerance level. This serves to avoid fatal injuries. The collapsible energy absorption devices must also provide a long deformation path to reduce the deceleration of the protected occupants. Therefore, when evaluating the crashworthiness of an energy absorption device, great attention should be directed to its instantaneous crush force efficiency. This is given as:

\[ CFE = \frac{P_m}{\bar{P}} \]  

(1)

where \( P_m \) is the mean load, which has been calculated by averaging the loads during the post-crush stage. In addition, the stroke efficiency (SE) defined as the ratio between the stroke and the initial height [4]. The energy absorption capabilities can be assessed by the dimensional absorbed energy (E):

\[ E = \int_0^H P \, du \]  

(2)

where H is the stroke length and P is instant crushing load. A more realistic assessment can be obtained by comparing the specific absorbed energy (E_s), defined as the energy per unit mass of the specimen. This is given as:

\[ E_s = \frac{E}{M} = \frac{P_m (S - S_i)}{M} \]  

(3)

where M is the specimen mass, and S and S_i are the crush distances.

2.2.3. Microscopic Investigation

Microscopic Investigation was carried out on the cross-section and transversal-section of the samples by using a scanning electron microscope (Nova Nano SEM 450 FEI). Samples were gold coated and observed using an applied tension of 3 kV. The reason for carrying this analysis was to investigate the appearance of DPLF composites at micro level before and after the mechanical tests; this is important because it indicates how the DPLF behaves in different conditions.

3. Results and discussion

In order to evaluate the crushing damage of structures, it is essential to obtain the real load-end shortening path relationship. Therefore, the results of the quasi-static compression test on composites in different directions are presented. The results obtained from this experimental study can be divided into two parts. The first part considers the energy absorption mechanism, and the second one evaluates the crushing modes damage morphological analysis.

3.1. Load-displacement

Typical load–displacement curves for lateral A, lateral B, and axially directions crushed composite rectangular tubes are shown in Fig. 6a, 7a, and 8a, respectively. These curves can be divided into four sections. The first section shows the pre-crush stage. The second section describes failure initiation crush-stage, showing matrix cracks at the top end of the system. The load–displacement curve drops drastically, and the initial failure occurs. The third section shows post-crush stage. For the specimens in lateral A and axially directions, it can be noted that the post-crushing stage was more stable compared to the lateral B specimen. Lateral B shows complete collapse after the failure initiation crush-stage. This is attributed to the composite rectangular tube overlap area. The fourth section presents stable behavior after the post-crush
Fig. 8. Axial quasi-static crushing test. (a) Load-displacement curve, (b) Deformation history.

Fig. 9. DPLF/epoxy composite morphology (a) before crushing, (b) after crushing.
3.2. Crushing modes

DPLF unidirectional reinforced epoxy composites rectangular tubes fail in an accumulative style that may involve a combination of different failure modes such as fiber pull out, fiber breaking, matrix cracking, and fiber/matrix debonding. Therefore, lateral A-B and axially crushing failure mechanism have been observed. Failure modes were studied and presented using the image video snapshot taken while crushing the specimens. Deformation histories of the crushed tube in different directions are shown in Figs. 6–8, respectively. Three different crushing failure modes were observed during the test. These failure modes can be classified as:

1. **Mode I**: This failure mode is associated with the tubes crushed in lateral A-direction. The crack was observed to be initiated at the top corners due to the high-stress concentration. Then after, the cracks propagated longitudinally and resulted in spilling the top beam from the sidewalls of the rectangular tube. The fracture occurred caused a considerable drop in the tube's load carrying capacity, as shown clearly in Fig. 6 (Points 1 and 2). At the post-collapse...
stage, the load picked up again due to the right tube wall resistance, which represents the column effect. The other wall observed to slide outward, and the energy absorption mechanism is dominated by the friction resistance between the wall and the upper plate. On the other hand, the splaying mode was found to dominate the response of the energy absorption mechanism of the right wall, as shown in Fig. 6 (points 3, 4, and 5).

2. **Mode II**: In this failure mode and due to the fact that the contact area is large compared with the tubes crushed in lateral A-direction crack, the tube experienced expansion outward, as shown in Fig. 1, point 1. At the post-collapsible stage, the tube's start to slide toward the left side, while the other side experienced fracturing and the load carrying capacity recorded the lowest value among tested tubes. Fig. 7 (points 3, 4, 5 and 6) represents the post-collapse of the laterally B crushed tubes.

3. **Mode III**: In this mode, the energy absorption mechanism initiated at the top end of the composite rectangular tube. While, the tube top-end splaying outward and then fragmented, leading to a slight drop in the load carrying capacity as shown clearly in Fig. 8 (1a, b).

Fig. 13. Axial crush damage morphology (a) matrix cracking, (b) debonding, fiber core cell wall collapses and fiber fracture.

Fig. 14. The peak and average crushing loads.

Fig. 15. The stroke and crushing efficiency.
splaying, and splitting in lamina bundles, as shown in Fig. 8 (2, 3, 4, 5, and 6). Progressive crush failure mechanism exhibited highest load-carrying capacity mode.

3.3. Morphological analysis

Natural fibers derived from the plant is a bio-cellular material consists mainly of cellulose fibrils embedded in lignin matrix. Each fiber has a complex, layered structure, which contains a primary cell wall and three secondary cell walls. The thick middle layer of the secondary cell walls determines the mechanical properties of the fiber. It consists of a series of helically wound cellular micro-fibrils formed from long-chain cellulose molecules. Each cell wall is made up of three main components, which are cellulose, hemicelluloses, and lignin. Lignin-hemicelluloses acts as matrix while micro-fibrils (made up of cellulose molecules) acts as fibers [6,7]. It is also known that the DPLF fiber core area has a high degree of porosity and is formed by closed packing arrangement tube structure named vascular bundles. Accordingly, Fig. 9a shows the DPLF vascular bundle packed tube structure before crushing. This porosity promotes proper energy absorption and shows similar crushing damage mechanism like other good energy-absorbing cellular materials (honeycomb, foam, and wood). The plastic collapse and fracture are the most relevant cell failure mechanism. Fig. 9b shows the DPLF vascular bundle cell wall collapse and fracture after crushing. It is interesting to note that the energy absorption of natural fibers is affected by the fiber orientation. In the lateral direction, packing arrangement of thin-walled tubes makes the compressive strength higher than that in the axial direction as has been cited by Gibson and Ashby [8,9]. Fiber orientation in DPLF/epoxy composites rectangular tube is 90° in the lateral direction and 0° in the axial direction. DPLF fiber orientation affected the energy absorption and crushing modes damage. Figs. 6–8 support this explanation. Fig. 10 shows the lateral crush damage microscopic morphology. It is visible different crush damage characteristic between the inner and outer wall tube side. The SEM observations were made for the lateral crush test damage morphology shown in Fig. 11 fiber fracture by crack propagation and stress concentration in the inner side. Debonding and fiber pull out in the fiber core caused by ductile tearing in the outer side are the main lateral crush damage characteristics. Fig. 12 (a) shows the axial crush damage microscopic morphology. Delamination and fiber fracture are the main characteristics in the progressive failure mode. The SEM observations in Figs. 12b and 13a are clear evidence of matrix cracking, debonding, and fiber fracture. Fig. 13b shows cellular crushing damage (fiber core cell wall collapse and fractured) and fiber–matrix interface debonding.

3.4. Energy absorption capability

Effect of loading direction on the crashworthiness parameters of DPLF composite rectangular tubes are shown in Figs. 14–16. The specific energy absorbed ($E_s$) was computed using equations 2–3. Accordingly, the calculated $E_s$ absorbed by DPLF composite rectangular tubes found to be very much sensitive to the loading directions. Among tested specimens, laterally-A crushed tubes have recorded the highest load carrying capacity. On the other hand, axially crushed tubes have displayed the highest energy absorbed values of 10.3 J/g, while laterally-B crushed tubes have recorded the lowest value of 0.94 J/g. As is well known, laterally crushed structures exhibit different load-displacement behavior compared to the axially crushed specimens. However, the laterally-A crushed tubes has the same load-displacement behavior of axially crushed tubes. It is worth to mention that energy absorbed by DPLF composite tubes was found to be lower than tubes made of Biotex® natural flax fiber/HD-PE [25].

4. Conclusions

In this study, the crushing behavior of date palm leaf fiber/epoxy has been studied experimentally under quasi-static axial and lateral compressive load. Based upon the experimental results, the DPLF unidirectional reinforced epoxy composites rectangular tubes demonstrated to be a good candidate as eco-friendly materials for automotive application. On the other hand, loading direction significantly affects the crashworthiness parameters for the natural fiber reinforced composite rectangular tubes. Finally, among tested specimens, laterally-A crushed tubes have recorded the highest load carrying capacity.

Acknowledgments

The authors would like to acknowledge the financial support of the Qatar National Research Fund (a part of the Qatar Foundation) through the National Priorities Research Program NPRP 05-068-2-024.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compstruct.2019.111004.

References


E. Mahdih,⁎, D. Ochoa a, A. Vaziri b, E. Eltai a

a Mechanical and Industrial Engineering Department, College of Engineering, Qatar University, P.O. Box 2713, Doha, Qatar

b Mechanical and Industrial Engineering Department, Northeastern University, Boston, MA 02115, USA

⁎ Corresponding author.