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Numerical investigation of compressive behaviour of luffa-filled tubes

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The behaviour of luffa and luffa-filled tubes under uniaxial compression was investigated numerically using finite element analysis (FEA) and analytically by theoretical models. The FEA models were validated against experimental data. Parametric study was carried out using the validated FEA models to examine the effects of the density of luffa, the thickness to diameter ratio of tube and the cross-sectional topology of luffa core. It was found that the optimal density of the luffa as filler for the luffa-filled tubes was closely related to the optimal density of the luffa sponge. It increased with the increase of the thickness to diameter ratio of the tube. The cross-sectional topology of the filler material had a negligible effect on the specific energy absorption per unit mass even when the deformation pattern of the luffa-filled tube was changed from the diamond mode to the concertina one.

1. Introduction

Research on new environment-friendly materials is becoming increasingly important due to ever-rising concerns about pollution and sustainability. Biological materials, such as luffa sponge, are usually composed of relatively weak base materials like minerals and proteins which are easily degradable, bio-compatible, pollution-free, recyclable and energy efficient [1,2]. In a recent study [3], it is shown that the luffa sponge could potentially be used as an alternative sustainable material for various practical applications such as packaging, acoustic and vibration isolation, and impact energy absorption. The luffa sponge material can be easily obtained from luffa fruits and it is recyclable and biodegradable [4,5]. A further recent study [6] shows that luffa sponge is a light-weight cellular material with high specific energy absorption capacity. However, up to now little research has been conducted on the luffa sponge as a source of bio-fibres and bio-composites due to the lack of scientific data on the mechanical properties [3]. To investigate potential practical applications of luffa sponge material as well as luffa fibres, the authors have conducted tests for the mechanical properties of luffa fibres. With good understanding of the mechanical behaviour of luffa sponge through experiments, it is now applicable to perform finite element (FE) simulations to understand the physical properties more deeply and to explore further potential applications of luffa sponge materials.

In order to improve the energy absorption capacities of the conventional thin-walled structures, foam filling method [7,8] and sandwich technique [9] have been well established in recent years. Significant research efforts have been devoted to the understanding of crashing behaviour and energy absorption characteristics of various metallic foam-filled structures. Previous theoretical and experimental studies focused on the plastic deformation of partially filled tubes can be found in [10], and of full filled structures in [11]. For the foam-filled structures, the specific energy absorption is usually taken as the design criterion for lightweight requirements [12,13]. As reported, the foam density is a key factor affecting the energy absorption capacity of various thin-walled tubes with fillers [14]. Generally speaking, higher foam density leads to higher energy absorption [15], while higher density foam material usually results in higher weight. So finding the optimal density of the foam to fill the given tubes is an important work [16]. It is worth conducting an in-depth research to gain further insights into this design problem. There has been only limited knowledge on this topic [17–19]. As mentioned above, luffa sponge is a sustainable light-weight material with a considerable high specific energy absorption capacity. Therefore it could be an excellent choice as a filling material. The experimental investigations on luffa-filled tubes confirmed that the luffa-filled tubes are effective composite structures for energy absorption [20].

As noticed previously, the original luffa sponge columns have large voids with different cross-sectional topologies in the centre

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region to accommodate seeds, the influence of those topologies on its effectiveness as a core material for thin-walled structures is a key factor for designing luffa-filled tubes. With the shape memory effect of luffa sponge [21], the original luffa sponge can be shaped into any required shape to be used as core material for various applications. During the shaping process, there will be irregular large voids inside of the luffa sponge. One of the aims of present study is to investigate the effect of those voids on the mechanical characteristics of luffa-filled tubes. Furthermore, it is more comprehensive and efficient in time and cost to use numerical methods providing accurate simulations on scenarios where comprehensive results may be difficult to obtain through conventional experiments. Thus this paper aimed to addresses these design issues for luffa-filled tubes structures. The finite element analysis (FEA) of luffa sponges, tubes and luffa-filled tubes were carried out by ABAQUS and MATLAB software based on previous experimental results. The optimal density of the luffa filler was given by the numerical results as well as the theoretical analysis against varying thicknesses of the tube. The influence of topology of luffa sponge column on the specific energy absorption was studied using luffa-filled tubes. The results of current work were also extended to the topology effect of metallic foams.

2. FEA modelling of luffa-filled tubes

2.1. FEA model of luffa

In the present study, the specific energy absorption is of interest. ABAQUS/Explicit was used for investigating the luffa sponge columns. The crushing patterns and energy absorption capability of luffa sponge column during the axial compression process were examined.

Luffa sponge is an extremely light natural cellular material and its mechanical performance is achieved through its hierarchical structures. The geometric features of luffa sponge depend on several factors, such as the plant origin, weather condition, soil, and so on. It is impossible to build FEA model for luffa sponge columns with the exact hierarchical structures. Similar to other cellular materials, the mechanical properties and energy absorption capacity of luffa sponge can be represented in a homogenized manner. A crushable foam material model with solid elements provided by ABAQUS can be used to study the energy absorption capacity of luffa sponge column. The luffa sponge with a density of 41.3 kg/m^3 was taken as representative. A set of homogenized material parameters were obtained from experiments. The values of key parameters used in FEA for this representative luffa sponge are listed in Table 1. For other densities, the parameters can be obtained by using the following formulae [3]. The plateau stress σ_{pl} is calculated as

$$\sigma_{pl} = 2.656 \times 10^3 \rho_l^{1.22} \tag{1}$$

where ρ_l is the density of luffa sponge. The unit of stress is Pa and density is kg/m^3. The Young's modulus of luffa sponge material is measured from the slope of nominal stress–strain curves between 25% and 75% of the compressive strength.

Table 1
The material parameters for representative luffa sponge.

Density (kg/m^3)	Young's Modulus (MPa)	Poisson's ratio	Compressive yield stress ratio	Plastic Poisson's ratio
41.3	6.3	0.3	2.12	0

Note: For luffa sponge with different densities, Eqs. (1) and (2) were used to scale the strain hardening curve and modulus based on the value in this table. The plastic Poisson's ratio and the compressive yield stress ratio were all the same for luffa sponge with different densities in the FEA model. In the experiments, the plastic Poisson's ratio was close to zero for luffa sponge with a density of 41.3 kg/m^3 and it increased slightly with respect to the relative density and this slight increase was neglected in the FEA model. The compressive yield stress ratio is calculated according to the formula in ABAQUS manual.

$$E = 0.084 \times 10^6 \rho_l^{1.16} \tag{2}$$

When considering the energy dissipation capacity of luffa, the densification strain of luffa, ε_d, corresponds to the point where the stress starts to rise significantly.

$$\varepsilon_d = 0.68 - 0.00162\rho_l \tag{3}$$

The meshes of the luffa sponge column were determined by a mesh size convergence check. The final mesh is shown in Fig. 1a. Rigid bodies were created using the brick elements to model the compression platens. An automatic single surface contact algorithm was applied to the outer surface of luffa to avoid the initial penetration. Since our experiments were under quasi-static analysis, to ensure quasi-static loading in an explicit code, a similar procedure as used in literature [19] was conducted by applying a controlled velocity as:

$$v(t) = \frac{d_{\max}}{T}\left(1 - \cos\left(\frac{\pi}{T}t\right)\right) \tag{4}$$

where T is the total duration of the loading, $d_{\max}$ is the final displacement, and t is the time. From this formula, the velocity field (v) and acceleration are zero both at the start and at the end of the loading, and the loading takes place gradually. In this manner, the inertia effect in the numerical solution can be avoided and the loading can be treated as quasi-static.

2.2. FEA model of tube

The experimental specimens were made of waste tins which were cut into cylinders. The geometries of such a tube are: the length l = 50 mm, outer diameter D = 65 mm and wall thickness t = 0.09 mm, respectively. The strain hardening curve for plastic material model was obtained from experiments. Other parameters of the tube used in the FEA model are shown in Table 2.

Thin shell elements were used to simulate the tube and are slightly offset from the top surface of brick elements to avoid the initial penetration. Moreover, the hourglass control was used to eliminate spurious zero-energy modes for all the reduced

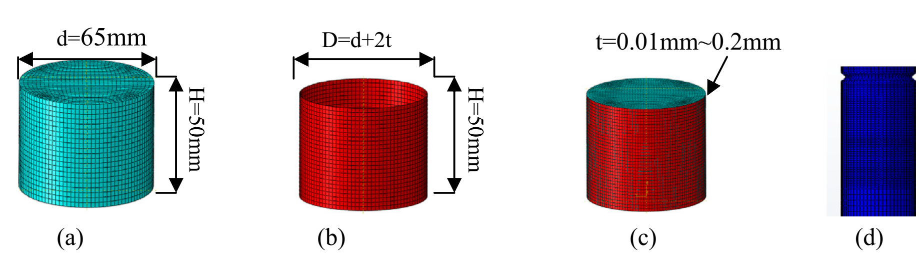

Fig. 1. Illustrations of the FEA models: (a) luffa; (b) tube; (c) luffa-filled tube; (d) metal foam filled tube with trigger [28].