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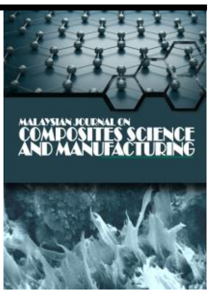

Investigating the Energy Absorption Characteristics of the Tropical Jackfruit (*Artocarpus Heterophyllus*) Inspired Sandwich Panel

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ABSTRACT

Different biological systems and objects have existed in nature in a best-fitted way for millions of years under various environmental conditions. These objects, with their extraordinary features, can be the design inspiration for engineers and scientists. Energy absorption characteristic is an important parameter for structures that safeguard human life and precious goods from accidental loading conditions. Moreover, sandwich panels, known for their excellent weight-to-stiffness ratio, are widely used for tailoring this purpose. In this study, a bio-inspired sandwich panel has been developed, drawing inspiration from the spiky structure of the outer shell of the tropical Jackfruit. The energy absorption characteristics and some other parameters are investigated using a computational approach and compared with two other types of structures (i.e., solid and hollow structures). The computational approach primarily entails a nonlinear static analysis that emulates a quasi-static compression test. Compared to the solid structure, the proposed biomimetic structure exhibits a mass and volume reduction of approximately 82% and 83%, respectively. The densification strain is also higher than the solid one, which ultimately increases the effective crushing distance for the proposed structure. In addition, the energy absorption (EA) and specific energy absorption (SEA) of the proposed biomimetic structure are approximately 4 and 2.5 times higher than those of the hollow structure. However, further investigations are required to justify its feasibility as an efficient energy absorber.

Keywords:
Bio-inspiration, Energy absorption, Sandwich panel, Jackfruit's shell, Spiky structure

1. Introduction

Nature possesses some outstanding features that outperform many contemporary designs and serve as inspiration for developing novel biomimetic structures. For instance, the invention of 'Velcro'

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in 1955 was the result of a Swiss engineer's inspiration from a plant's hook-like object clinging to his dog's fur. Now, it is widely used for everyday tasks to astronaut's space suits [1-2]. Another thought-provoking phenomenon in nature is woodpecker's pecking and how it avoids brain injury while pecking at a deceleration of 1000g (10000 ms^{-2}), several times higher than that of the human brain can tolerate, which is thoroughly investigated by May *et al*. [3] and Gibson [4].

Goods are packaged inside the packaging structure to prevent damage, even when we are also packaged inside vehicles such as automobiles, aircraft, submarines, etc. [5]. So, explaining the importance of finding and selecting the perfect energy-absorbing structure that ultimately builds a safer and more efficient packaging structure is needless.

Fortunately, nature provides many highly efficient energy-absorbing structures that can inspire our scientists and engineers. Keratin, one of the toughest materials found in nature, serves different applications like defence against predators, competing for territory, protection against the environment, and so on, by forming the organs of the animal kingdom like hooves, horns, beaks, nails, feathers, etc. These keratinous structures, classified into α-keratin and β-keratin, are thoroughly studied by Wang *et al*. [6]. The ability of beetle forewing to resist puncture (up to 23 N) against external forces offers valuable insights for the study of lightweight composite material [7]. Ghazlan *et al*. [8] extensively reviewed how inspiration can be derived from nature's body armour to develop highly efficient bio-inspired armour systems. The researchers elaborately reviewed the implementation of these defensive features of the animal kingdom and other bio-inspired structures through additive manufacturing technology [9-12].

Cellular structures are widely used as energy-absorbing structures due to their lightweight nature and high porosity. Synthetic foams like metallic and polymer foams are common in everyday life but abound in nature, too. One of the most common examples is the pomelo (*Citrus maxima* or *Citrus grandis*) fruit. It can dissipate 90% of its kinetic energy while falling from a tree (15 m), keeping the pulp and seeds intact [1]. Researchers have tried different ways to capture its excellent damping properties by implementing the hierarchy of this natural structure. Fischer *et al*. [13] worked with the casting process to develop metallic foams, and Schäfer *et al*. [1] analyzed the feature through numerical modelling of foam samples (kelvin cell). The first scientific study on luffa [14], a lightweight open-cell cellular structure, reveals that it has a constant plateau over a long strain range, which is one of the prerequisites for being an ideal energy absorber. The densification strain and energy absorption efficiency are 0.57 and 0.45 (*approx*.), respectively. The study by Shen *et al.* [14], also demonstrated that under uniaxial compression, its energy absorption per unit mass is identical to that of other aluminum foams and most polymer foams. Finally, they proposed this for alternative packaging materials due to their extremely lightweight nature, environment-friendly behavior, and sustainability.

Lightweight energy-absorbing structures, such as sandwich panels, hold significant potential in various fields like aerospace, packaging industries, etc. Many researchers studied such properties with different core configurations and material properties. With that trend, the mechanical properties of paper honeycomb sandwich panels are exploited by Wang *et al*. [15]. Paper honeycomb is used widely in packaging applications due to its excellent cushioning properties and lightweight characteristics. The hierarchical or gradient structure shows greater possibilities for tailoring customized mechanical properties for impact protection or other loading conditions. Porous spongy pomelo peel is another example. In the albedo (mesocarp), the vascular bundles are densely located. Zhang *et al*. [16] applied this hierarchical configuration to the honeycomb structure. They found that the specific energy absorption (SEA) and the equivalent plateau stress are 1.5 (out-of-plane) and 2.5 (in-plane-crushing) times higher than that of the conventional honeycomb. Another interesting study was conducted by Ha *et al*. [17], where a bio-inspired honeycomb sandwich panel (BHSP) was proposed, and the design inspiration came from the microstructure of a woodpecker's beak. The TEM imaging shows that the upper beak's keratin grain structure is composed of tightly packed honeycomb cells, and the cell walls are wavy in configuration (assumed to be a sine wave structure). Finally, it is found that for the same thickness and volume of the core, the proposed structure has 125% and 63.7% higher specific energy absorption (SEA) capability than that of the conventional honeycomb sandwich panel (CHSP) [17].

Moreover, a study by Ha *et al.* [18] was conducted for the first time to determine the mechanical properties and energy absorption characteristics of the tropical fruit known as durian. The fruit has a distinctive spiky outer shell and remains intact even when it falls from a height of 15 m. The exocarp (spiky) and mesocarp had been brought under a quasi-static compression test to investigate their properties. The densification strain found for the mesocarp-exocarp layer under axial loading is 0.64 (*approx*.). They proposed the half durian shell for bio-inspired goods packaging and helmet structure [18]. Furthermore, several researchers illustrated a detailed view of biomimetic structures and materials studies [8, 19-20]. Like durian, another tropical fruit is jackfruit, which has the same spiky outer shell but a different geometrical configuration. Unlike durian [18], there hasn't been similar research on jackfruit, making it a promising area for studying its energy absorption characteristics for the first time.

The current study has designed a sandwich panel with a spiky core like the jackfruit's outer shell. Each spike has a hexagonal cross-section and is hollow inside, reducing the weight significantly. Later, it is compared with two other structures (one entirely solid and the other hollow inside) via quasi-static compression simulation. Finally, the three structures are evaluated based on some parameters related to energy absorption characteristics. Indeed, the study could improve society by creating a reliable protective structure, ensuring safety and smoothness in daily living.

2. Materials and Methods

2.1 CAD Models

All three samples were prepared using the 3D modelling software 'SOLIDWORKS'. They possess the same outer dimensions, i.e., $(10 \times 10 \times 3)$ mm and outlook, i.e., an enclosed rectangular box with different core structures. The three structures are illustrated below in Figure 1, Figure 2, and Figure 3.

Among the depicted figures, Figure 1 shows the solid block, Figure 2 shows the hollow block with a wall thickness of 0.1 mm, and Figure 3 shows the biomimetic sandwich panel with a spiky core structure with a wall thickness of 0.1 mm. In every structure, there are three different parts: the top part applies the compressive force, the middle part is the specimen, and the bottom part gives fixed support to the specimen.

The specimen is modelled using aluminium alloy AA6060, with steel specified for the top and bottom parts. Stress-strain data beyond the yield point is required for aluminum, and that is obtained from the literature to capture the nonlinearity of the analysis [21].

2.2 Simulation Setup

The simulation is done on the cloud platform named 'SimScale'. This is a displacement-controlled uniaxial compression test simulation, and the analysis type is static structural nonlinear. Bonded contact is applied to hold the specimen in the exact position, and physical contact is applied with a specific penalty coefficient to avoid interpenetration. As the boundary conditions, displacement is applied onto the top face of the upper part, and fixed support is applied at the bottom face of the lower part. 1st order tetrahedral element has been used for meshing the structure. Mesh refinement has been done on specific regions to attain the accuracy of the data. The displacement is applied in 20 steps as a function of time, and the structure is deformed in each step by 0.09 mm. Finally, the solution fields have been created to extract the result data, i.e., the reaction force to deform the structure, corresponding displacement, stress, and strain data based on a specific point on the structure.

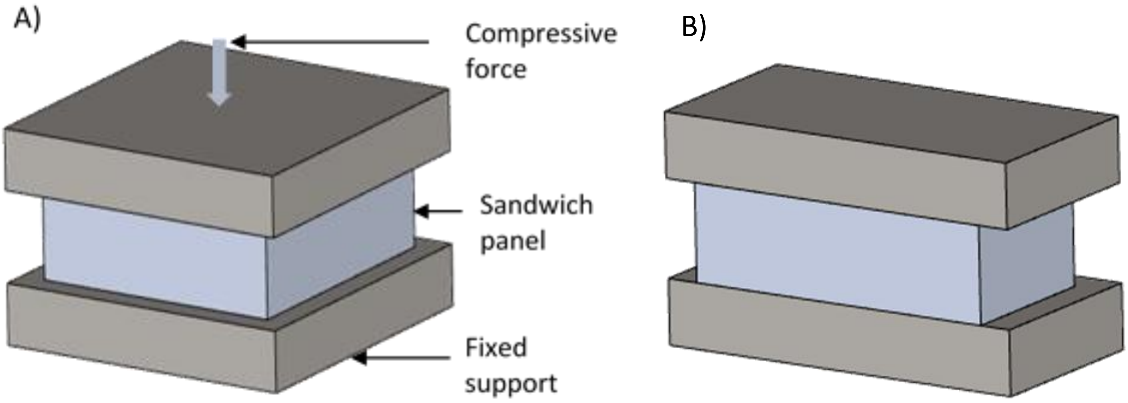

Fig. 1. (A) Sandwich panel having a solid core, and (B) A cross-sectional view of the panel

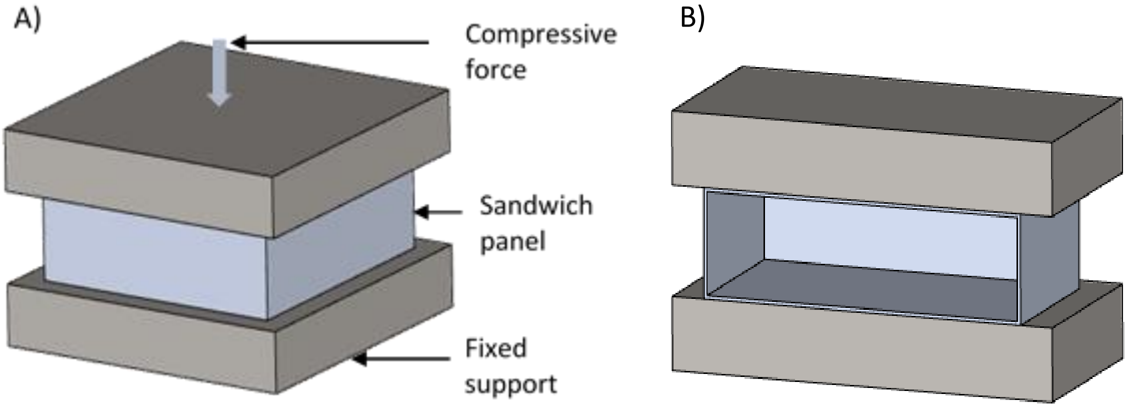

Fig. 2. A) Sandwich panel with a hollow inside, and B) cross-sectional view of the panel

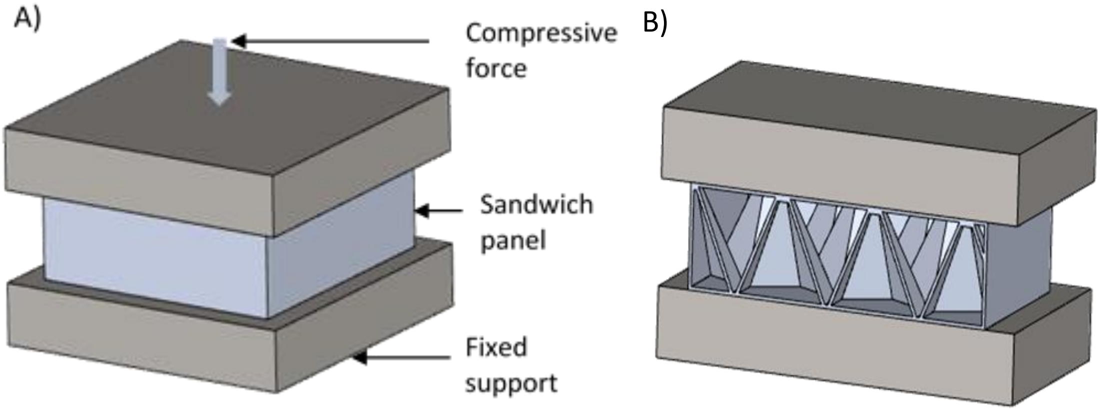

Fig. 3. A) Proposed biomimetic sandwich panel, and B) cross-sectional view of the panel

3. Results and Analyses

3.1 Force vs. Displacement Curves

The force vs. displacement curves are obtained for 60% deformation of the structures, i.e., 1.4 mm. Maximum energy absorbed up to 60% deformation is determined by calculating the area under the curve. That is done using the formula of energy absorption (EA) in Eq. 1:

$$EA = \int_0^{d\_max} F(x)\,dx \tag{1}$$

where, $F(x)$ is the compressive force along the displacement x and the 'd_max' is the maximum effective deformation before entirely crushed.

Specific energy absorption (SEA) is evaluated to compare the findings in terms of weight. It is defined as how much energy is absorbed per unit mass and is calculated as in Eq. 2:

$$SEA = \frac{EA}{m} \tag{2}$$

here, m is the mass of the structure.

Force versus displacement curves for the solid block, the hollow block, and the proposed sandwich panel are shown in Figures 4, 5, and 6, respectively.

Figures 4 - 6 show that the force varies linearly up to a small displacement. Elastic deformation of the structure occurs in this region and can regain its original shape upon unloading. Then the curve grows very slowly up to a point and again starts rising sharply. The middle flat and smooth portion of the curve denotes the plastic deformation of the structure, and the subsequent rise of the curve denotes the ultimate collapsing of the structure or the densification. However, the force decreases gradually for the hollow structure and comes to a steady condition. This may be due to the large void inside the structure, and only the very thin wall of 0.1 mm at the periphery cannot support the compressive force considerably.

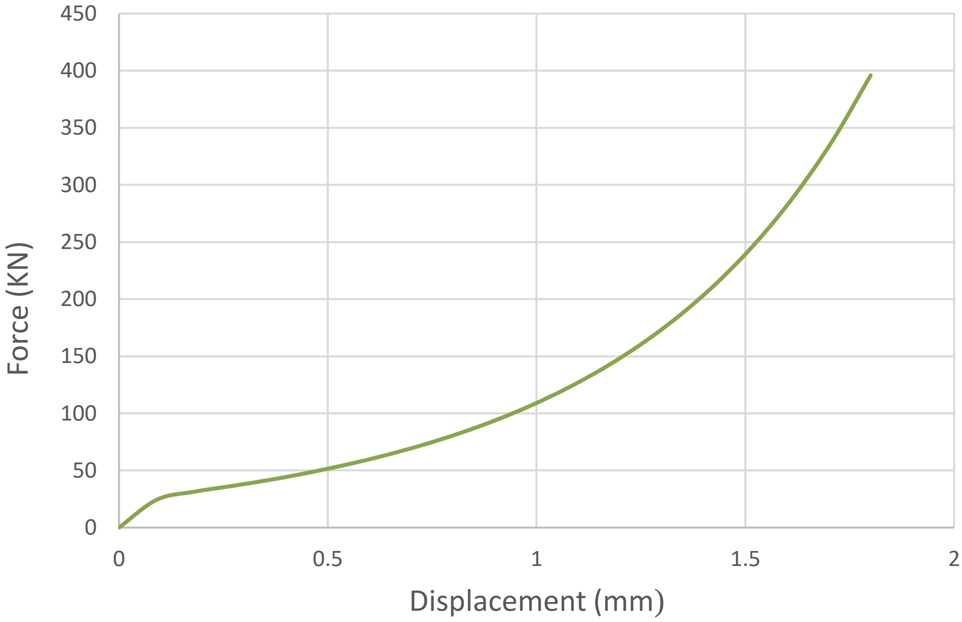

Fig. 4. Force versus displacement curve for the solid structure

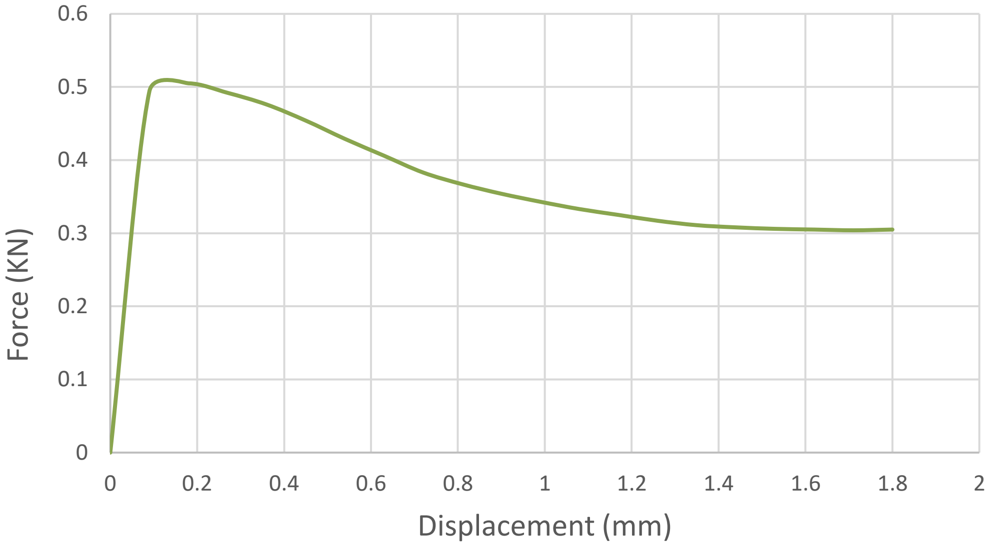

Fig. 5. Force versus displacement curve for the hollow structure

Maximum energy absorbed up to 60% deformation by the solid structure, i.e., 231 Joule, is significantly higher than that of the other two, i.e., 0.663 Joule for the hollow one and 2.92 Joule for the biomimetic one. Similarly, it is also true for specific energy absorption (SEA). The specific energy absorption for the solid structure is 285 KJ/Kg; for the hollow and biomimetic one, it is 8.29 KJ/Kg and 20.86 KJ/Kg, respectively.

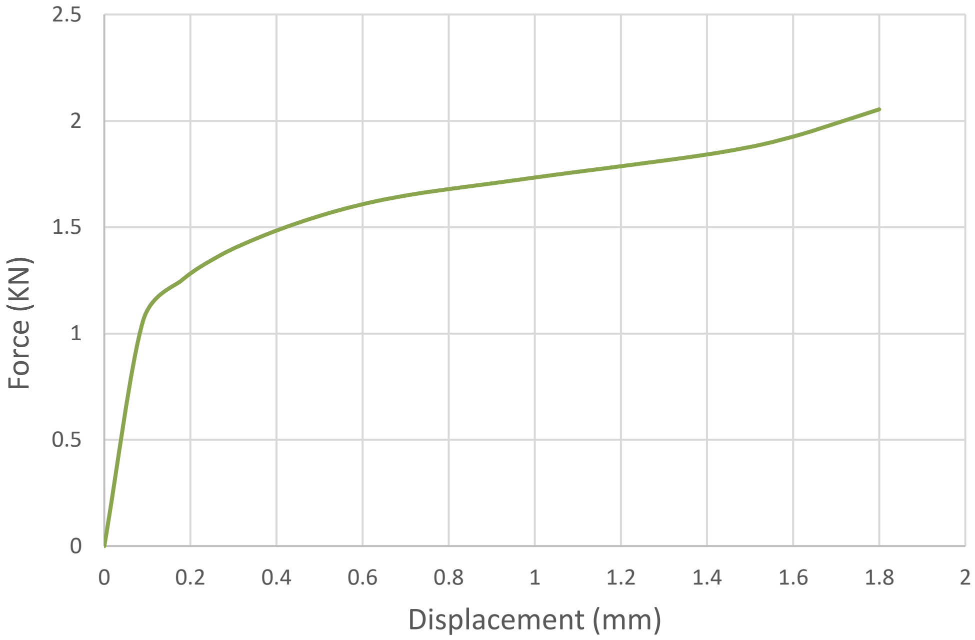

Fig. 6. Force versus displacement curve for the biomimetic sandwich panel

3.2 Stress vs. Strain Curves

Here, the stress-strain curve plots are represented for 80% deformation of the structure to better grasp the three distinctive regions generated from a compression test, i.e., the linear elastic region, plateau region, and the densification region. The force-displacement curves showed that the maximum energy absorption by the hollow structure is significantly low, and there is no tendency to raise the force again up to that specified deformation. Rather, for the solid and biomimetic one, after the flat middle portion of the curve, a new deformation mechanism initiates that is indicated by the sharper rise of the force. Since the solid structure outperforms the other two structures, it will be prudent to compare it by some other parameters. That's why the study here proceeds with the solid and biomimetic structure rather than the hollow one.

After the yield point, the structure deforms plastically and, in the force versus displacement curve, this mechanism continues up to a critical strain called densification strain. Most of the compressive load is absorbed in this region. The critical strain (ε_{cd}) needs to be calculated to realize how long the structure will absorb the energy efficiently. There is a method proposed by Li *et al.* [22] to determine this strain. According to this method, the onset strain of densification is at the point where the maximum energy absorption efficiency will be attained. The energy absorption efficiency (η) is calculated using the formula in Eq. 3:

$$\eta = \frac{\int_0^{\varepsilon_a} \sigma \, d\varepsilon}{\sigma_a} \tag{3}$$

where, σ_a is the corresponding stress for a particular strain ε_a.

The condition of maximum efficiency is satisfied by the following formula in Eq. 4:

$$\frac{d\eta}{d\varepsilon}\Big|_{\varepsilon=\varepsilon_{cd}} = 0 \tag{4}$$

The stress versus strain curves for the solid and biomimetic structures are represented in Figures 7 and 8, respectively.

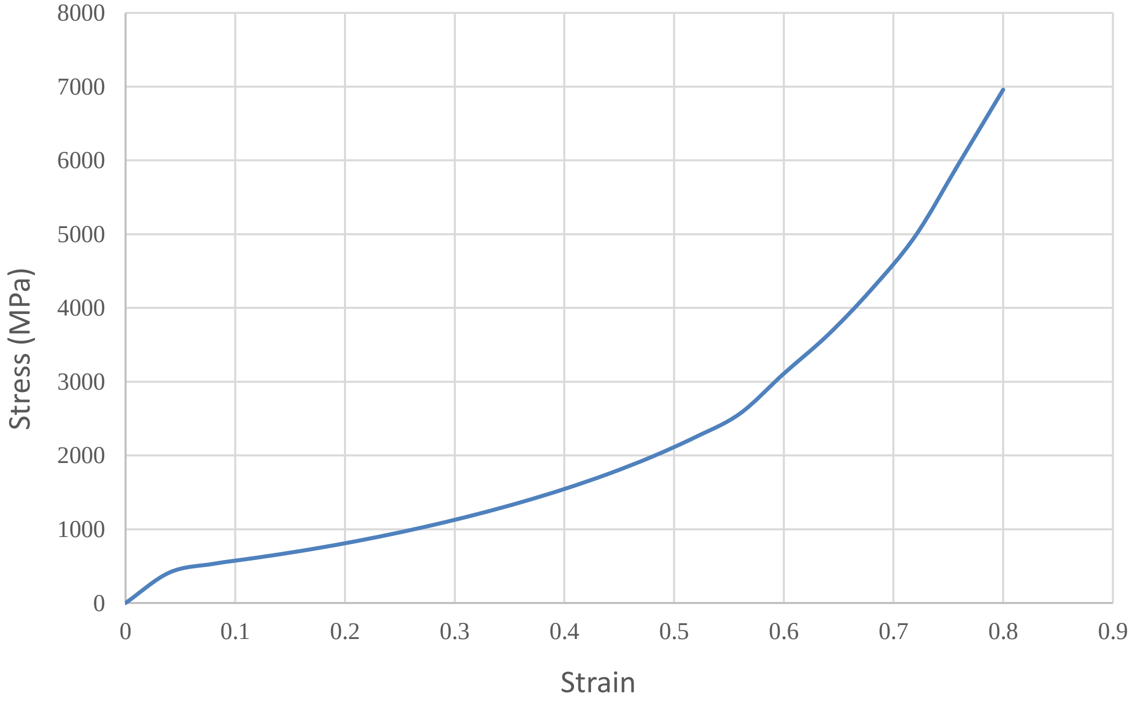

Fig. 7. Stress versus strain curve for the solid structure

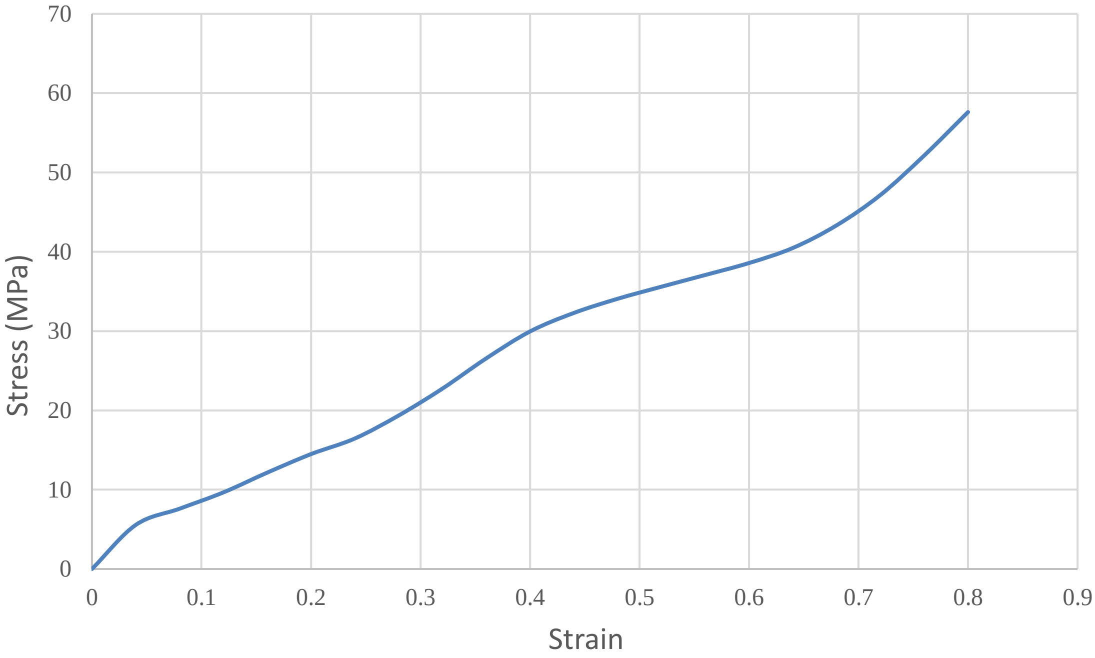

Fig. 8. Stress versus strain curve for the biomimetic structure

The stress-strain curve for the solid one resembles the ideal stress-strain curve of a compression test with the three distinctive regions. However, for the biomimetic one, a secondary plateau region is apparent. This condition is probably due to the partially shorter spikes positioned along with the periphery that do not come into contact with the top face at the beginning of the compression; a few later, it does, and then this secondary region happens. The energy absorption efficiency (25.61%) and the densification strain (0.56) are both lower for the solid structure than the biomimetic structure, i.e., 38.47% and 0.8, respectively. These two data are comparable with the literature (luffa [14] and durian [18]). Finally, it is noteworthy that the mass and volume of the solid structure (0.81 g and 300 mm^3) and is considerably higher than that of the hollow (0.08 g and 31.09 mm^3) and the biomimetic one (0.14 g and 51.23 mm^3).

4. Discussions

It is apparent from the analysis that the energy absorption and specific energy absorption are higher for the solid structure. However, if the mass and volume are considered, the proposed biomimetic structure is much lighter than the solid one. Moreover, from the stress-strain plots, it is evident that a secondary plateau region prevails for the biomimetic structure that may contribute to a steady and stable crushing of the structure. Catastrophic deformation of a protective structure could cause potential damage to the surrounding supporting structure and, consequently, the objects being protected by such structures. It is also obvious from the force versus displacement curve that the effective deformation distance is lower for the solid structure. In contrast, at the same crushing distance, the biomimetic structure still has the potential to absorb energy. While compared with the hollow structure, the proposed biomimetic structure performs far better in both energy and specific energy absorption. The following bar charts in Figure 9 and Figure 10 can represent the overall findings to visualize the comparisons better.

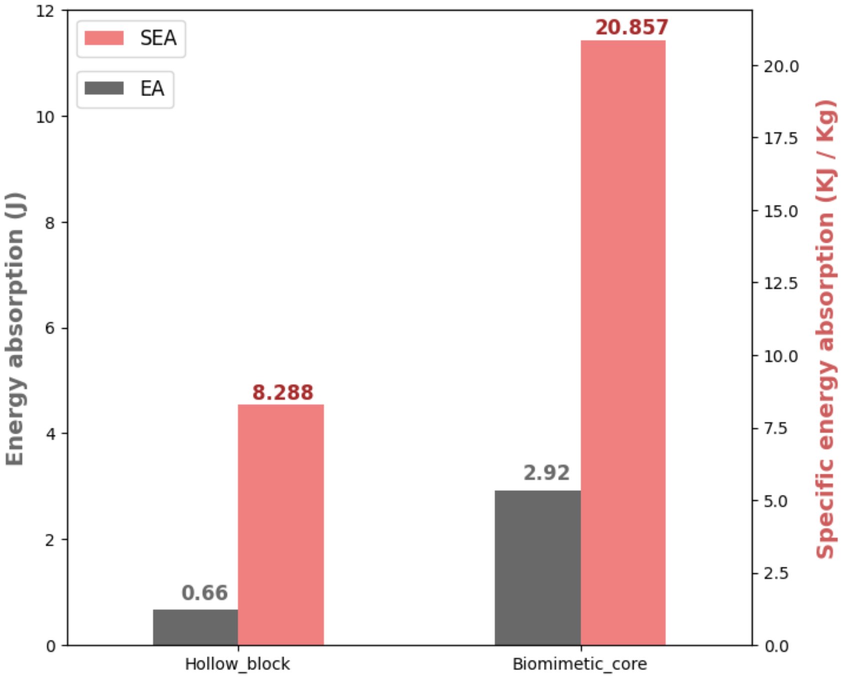

Fig. 9. Comparison between the hollow and the biomimetic structure in terms of EA and SEA

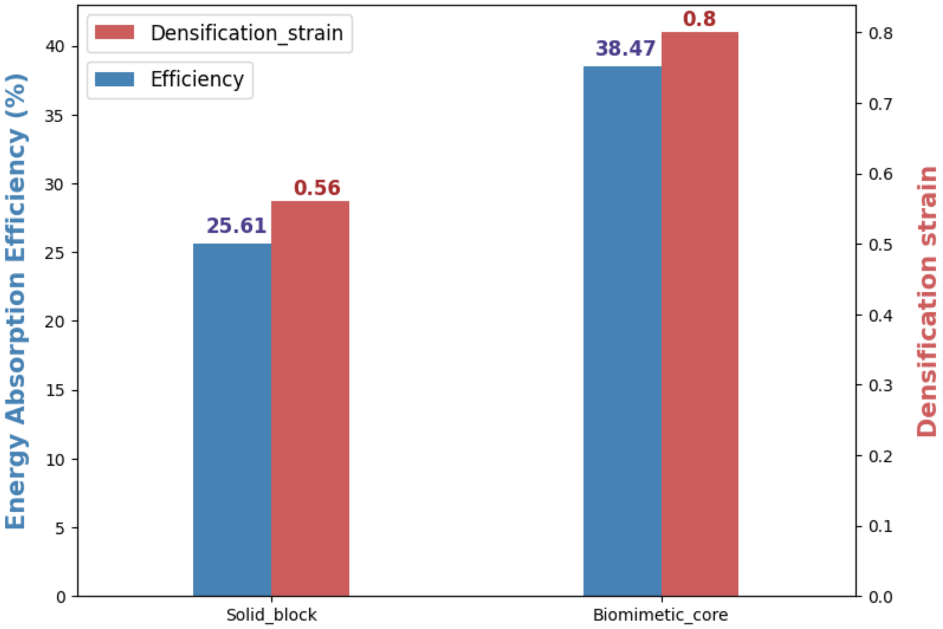

Fig. 10. Comparison between the solid and the biomimetic structure in terms of EA efficiency and densification strain

5. Conclusions and Future Study

The present study was initiated by designing a sandwich panel with a core structure mimicking the jackfruit's spiky shell. Afterwards, the energy absorption characteristics and other properties are determined through a computational approach to evaluate and compare the proposed design with two other types of structures. Finally, it is found that the proposed biomimetic sandwich panel is a lightweight structure and exhibits a promising trend to efficient energy absorption with the progress of deformation. It can be concluded that the proposed structure might be used after adequate optimization where the lightweight nature is the dominating factor alongside the energy absorption characteristics.

The computational approach paves a great way to exploit the hidden potential of nature by designing and modelling its unique features. However, validation of such a study is required to make it acceptable and reliable. Additive manufacturing, prominent nowadays, comes in handy in this case. With numerous design iterations, a model could be developed, and researchers could have real data on their model through hands-on experiments. The model used in the current study is simplified; hence, further investigation could be carried out by changing the geometric configuration, e.g., wall thickness, core thickness, solid spikes instead of hollow ones, spikes with intermediate height to make the deformation stable, and so on. The concluding remark is that engineers and scientists can draw inspiration from nature and implement these insights to build a safer, greener and sustainable world for humankind.

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