Benefiting from biomimicry through 3D printing to enhance mechanical properties of polymeric structures: Simulation approach

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Abstract. Numerous biological structures have intricate compositional arrangements, well-organised pieces and stronger mechanical qualities than the materials that make them up. Therefore, this study focused on enhancing the mechanical characteristics of three-dimensional (3D)-printed acrylonitrile butadiene styrene (ABS) structures. Selected parts/systems of three natural (animal/plant) materials were designed/modelled and analysed to mimic their natural lattice structures (biomimicry), using CATIA V5 and finite element method/Ansys software. The simulation results showed that the tensile strength of the biomimetic-designed beetle increased by 13.63%, the bending strength of the biomimetic lotus stem improved by 2.00 and 19.86% in simple and three-point bending tests, and the compressive strength of biomimetic trabecular bone enhanced by 87.59%, when compared with their conventional structures. Also, the biomimetic design recorded 10.00% higher compressive strength than a fillet design and nearly 64.00% than the repeated pattern. It was evident that biomimetic designs enhanced the mechanical properties of all the 3D-printed ABS structures.

Keywords. Biomimicry, 3D printing, Mechanical properties, Polymeric structures.

1. Introduction

The term *biomimicry* is obtained from two ancient Greek words: *bios* - means life, and *mimesis* implies - to imitate. A useful idea, known as biomimicry, uses ideas from nature to create sustainable solutions to human issues [1]. It is a method that takes cues from and imitates the tactics employed by current-day species as well as other aspects of the natural world. The objective is to develop sustainable structures, procedures and regulations or new ways of living that address our biggest design problems and benefit all forms of life on earth. It is clear from history that techniques resembling the concept, such as designs drawn from nature, existed before the term biomimicry became widely accepted. One of these examples is Leonardo da Vinci's initial model of an aero plane, which was motivated by the flying of birds [2]. Therefore, this study investigated into the possibility of improved mechanical properties (tensile, bending and compressive strengths) of three-dimensional (3D)-printed acrylonitrile butadiene styrene (ABS) structures, leveraging biomimicry, finite element analysis (FEA) and additive manufacturing (AM) technology.

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2. Biomimetic designs

2.1. Biomimetic designed suture structure of beetle

The suture structure of *Phloeodes diabolicus* (beetle) was design to mimic the natural type, using CATIA V5 software similar to all other biomimetic plant/animal parts studied within the scope of this work. Beetle has suture structure in its upper skin, which exhibits the outstanding mechanical properties, especially tensile strength. Figure 1(a) shows the image of a beetle and its microscopic suture structure. Figures 1(c) and (c) depict the biomimetic designed sutures. Due to this structure, beetle can bear a high amount of load.

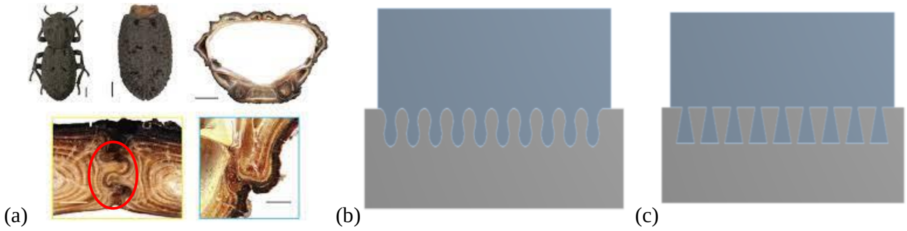


Figure 1. (a) *Phloeodes diabolicus* beetle and its suture structure (inside red ring) [3], (b) biomimetic and (c) triangular designed sutures.

2.2. Biomimetic designed lotus stem structure

This biomimetic design of lotus stem with diameter of 40 mm and length of 150 mm was modelled from the inspiration of natural lotus stem (Figures 2a and b). While, Figures 2(c) and (d) show its biomimetic and circular designed models, respectively. Lotus stem has many holes and porosity. This porosity serves different purposes for the lotus, it increases its bending strength. Therefore, a bending test was simulated to check its behaviours under different bending conditions.

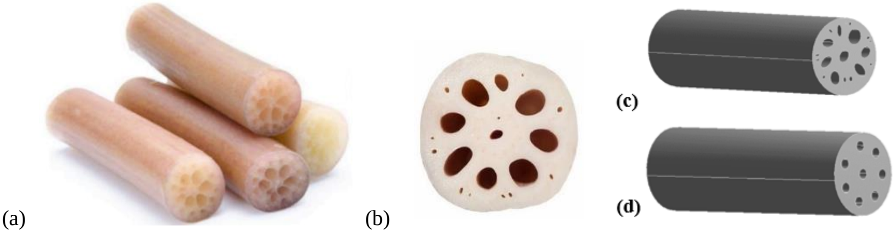


Figure 2. (a) Lotus stem, (b) its internal structure [4], (c) biomimetic and (c) circular models. .

2.3. Biomimetic designed trabecular bone structure

The intricate cellular composition of trabecular bone has excellent and lightweight energy absorption properties. Engineered cellular structures can be progressed into a new generation of protective systems by replicating this revolutionary high-performance structure. Complex evolutionary processes have honed complicated structure of bone to reduce weight, increase mobility and achieve the cyclic stress requirements of the human body [5]. Hence, inspiration was taken from this structure by mimicking its cellular pattern, as shown in Figure 3.

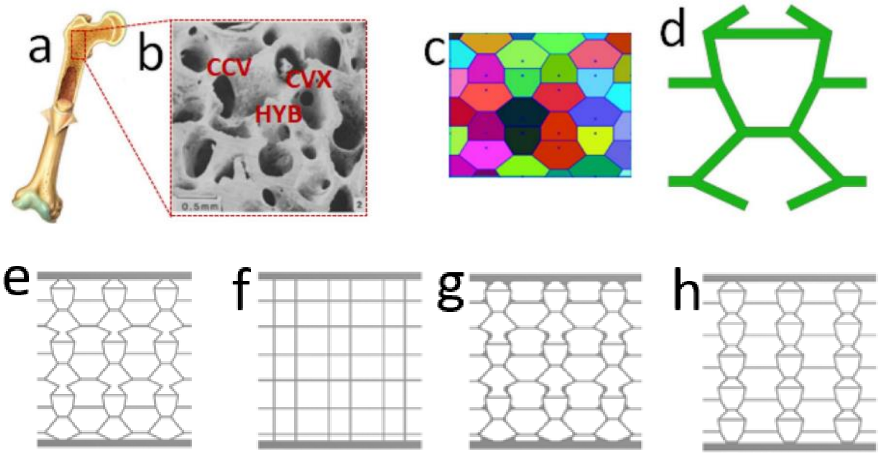
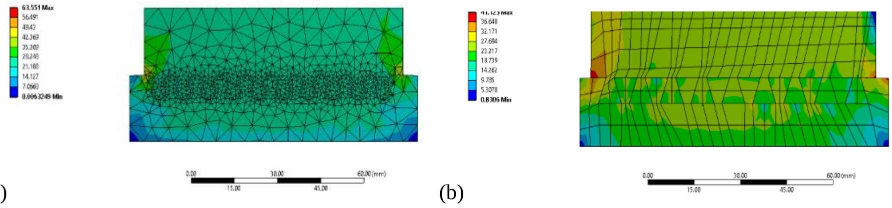


Figure 3. (a) Bone trabeculae, (b) trabecular bone closed cell plate-like structure, which was made up of (c) a Voronoi diagram that mimics trabecular bone, (d) a unit cell that was taken from the Voronoi diagram [5], (e) biomimetic, (f) square, (g) fillet and (h) repeated designs.

3. Simulation results and discussion

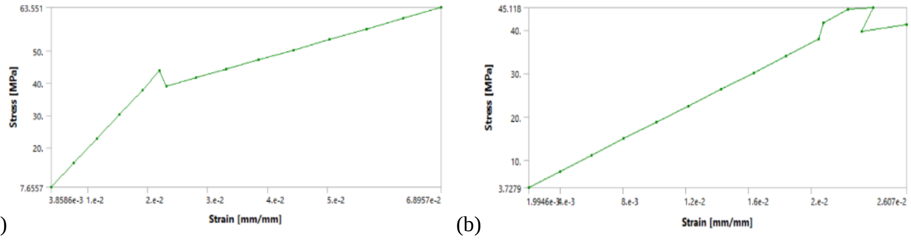
3.1. Biomimetic suture structure of beetle

The exact pattern of suture was mimicked to design and simulate two plates, which were joined by suture structure, as shown in Figures 4 (a) and (b). Figures 4 (a) and (b) depict the simulated biomimetic and triangular models. The thickness, total height and overall length of the plate were 2, 40 and 100 mm respectively. The total height included the height of both plates. The circle diameter of the suture pattern was 5 mm. Tensile load of 5 kN was applied at the top surface of the model. Fixed support was applied at left, right and bottom surface of the lower plate. Static structural analysis was performed. Figures 4(a) and (b) show the stress distribution region after FEA, whereas Figures 5(a) and (b) depict stress *versus* strain plots of biomimetic and triangular designs, respectively. Table 1 presents of tensile strengths of both designs, implying that biomimetic design exhibited a higher tensile strength than triangular type.



(a) (b)

Figure 4. Stress distribution in (a) biomimetic and (b) triangular designs under tensile load.



(a) (b)

Figure 5. Stress *versus* strain plot of (a) biomimetic and (b) triangular designs under tensile load.

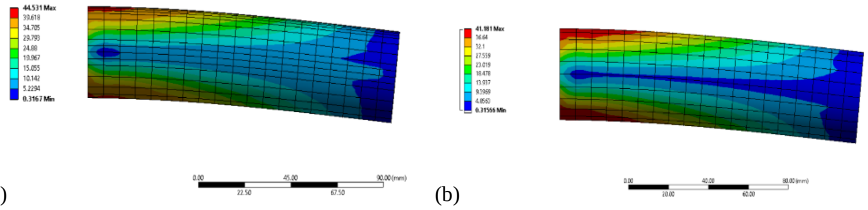
Table 1. Tensile strengths of the biomimetic and triangular suture structures of beetle.

S/No	Design/model	Tensile strength (MPa)	Minimum safety factor	Rank
1	Biomimetic	43.839	0.582	1st
2	Triangular	37.860	0.899	2nd

3.2. Biomimetic lotus stem structure

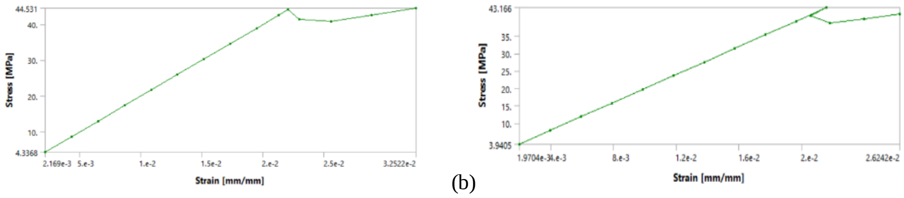
Firstly, a simple bending test was simulated, whereby the left side of the model was kept fixed and load of 2 kN was applied at the right face in downward direction. Secondly, a three-point bending analysis was also simulated on both designs similar to the first case. The left and right sides of the stems were kept fixed and the same load of 2 kN was applied at their middle.

There were eight holes in the circular design with size of 5 mm, each. All dimensions of the designs were kept same with that biomimetic design. Figures 6 and 8(a) and (b) show the stress distribution region and Figures 7 and 9(a) and (b) depict the stress *versus* strain plots for simple and three-point bending tests, respectively. In addition, Table 2 presents the bending strengths for both designs, whereby biomimetic design recorded higher bending or flexural strengths when compared with the conventional circular design under both normal/simple and three-point bending loadings.



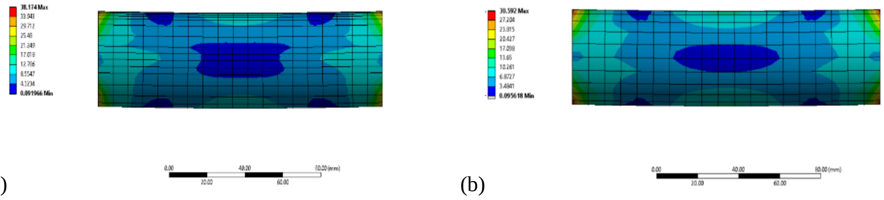
(a) (b)

Figure 6. Stress distribution in (a) biomimetic and (b) circular designs under simple bending load.



(a) (b)

Figure 7. Stress *versus* strain plots for (a) biomimetic and (b) circular designs under simple bending load.



(a) (b)

Figure 8. Stress distribution in (a) biomimetic and circular designs under three-point bending load.

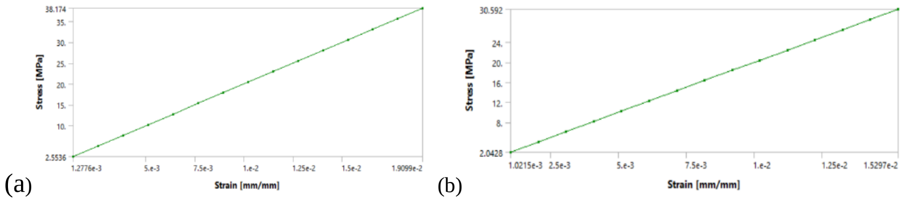


Figure 9. Stress *versus* strain plots for (a) biomimetic and circular designs under three-point bending load.

Table 2. Bending strengths of the biomimetic and circular lotus stem structures.

S/No	Design/model	Bending strength (MPa)		Rank
		Simple	Three-point	
1	Biomimetic	44.050	38.174	1st
2	Circular	43.166	30.592	2nd

3.3. Biomimetic trabecular bone structure

A compressive test was simulated under a load of 1.2 kN at the top of the various models. The lower surface of the design was kept fixed. Figures 10(a)-(d) show the FEA (stress distribution) of the biomimetic design, other square, fillets on all edges and repeated patterns, respectively. All dimensions, such as overall height, width and thickness, were kept same for all the four different models. Figures 11(a)-(d) depict the stress versus strain plots of all the four designs, while Table 3 presents the compressive strengths of the various designs. It was observed that the biomimetic design exhibited the highest compressive strength of 50.266 MPa, followed by the fillet pattern with a compressive strength of 45.538 MPa, when compared with other designs. The lowest or minimum value of 6.238 MPa recorded by the square design can be attributed to the highest stress concentration at its four edges or corners, causing premature material fracture under linear compressive loading.

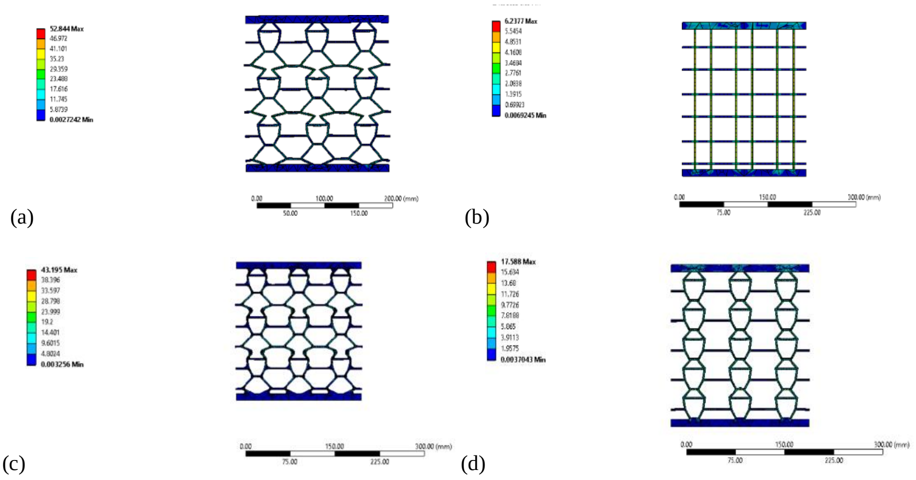
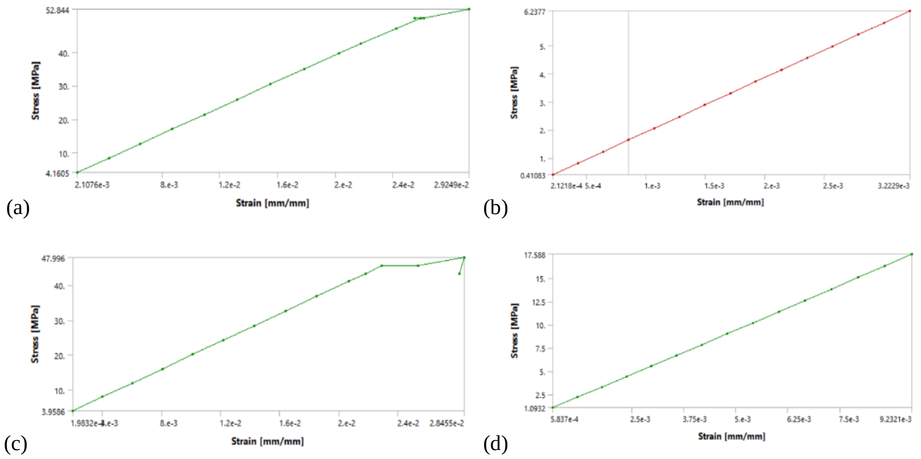


Figure 10. Stress distribution in (a) biomimetic, (b) square, (c) fillet and (d) repeated designs under compressive load.



(a) (b)

(c) (d)

Figure 11. Stress *versus* strain plots for (a) biomimetic, (b) square, (c) fillet and (d) repeated designs under compressive load.

Table 3. Compressive strengths of the biomimetic and other designs of trabecular bone structures.

S/No	**Design/model**	**Compressive strength (MPa)**	**Rank**
1	Biomimetic	50.266	1st
2	Square	6.238	4th
3	Fillet	45.538	2nd
4	Repeated	17.588	3rd

4. Conclusions

The improved mechanical properties (tensile, bending and compressive strengths) of 3D-printed ABS structures have been studied, using simulation approach as well as leveraging on both biomimicry and AM technology. Biomimetic designed beetle, lotus stem and trabecular bone were considered. From the results obtained, the following concluding remarks can be deduced.

The biomimetic structure of beetle recorded higher tensile strength, lotus stem exhibited better simple and three-point bending/flexural strengths and trabecular bone had greater compressive strength when compared with simple/conventional structures. Hence, mechanical properties of engineering structures can be improved based on biomimicry and using AM technology to support several structural applications.

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