Ref: Submitting my revised manuscript entitled "**Biomimetic Design and Topology Optimization of Discontinuous Carbon Fiber-Reinforced Composite Lattice Structures**" to the Special Issue of Biomimetics on "Bionic Engineering for Boosting Multidisciplinary Integration"

Date: March 31st, 2023

Dear Ms. Dolly Liu and editorial office staffs:

I greatly appreciated you, the editorial board staffs and especially the reviewers for taking time to review my manuscript and providing me with valuable guidance, advice, and comments. I have made changes accordingly, and I am enclosing herewith my revised manuscript entitled "**Biomimetic Design and Topology Optimization of Discontinuous Carbon Fiber-Reinforced Composite Lattice Structures**". Enclosed please find the revision details of the point-by-point list of the response to the reviewers' comments for your review.

Abstract: *The requirements for the continuous growth of structural performance drive the research and development of lighter, stronger, tougher, and multifunctional composite materials, especially, the lattice structures, heterogeneities, or hybrid compositions are of significant interest to the material research community. If it is pushed to the extreme, these concepts can be composed of lattice structures that are highly controlled by bio-inspired material design and topology optimization (TO). However, the strong coupling among the composition and the porous microstructural topology hinders the conventional trial-and-error approaches. In this work, discontinuous carbon fiber-reinforced polymer matrix composite materials were adopted for structural design. A three-dimensional (3D) periodic lattice block inspired by the cuttlefish bone, combining computer modeling based topological optimization was proposed. Through computer modeling, the complex 3D periodic lattice blocks with various porosities were topologically optimized and realized, and the mechanical properties of the topological optimized lattice structures were characterized by computer modeling. The results from this work were compared with other similar designs and experiments to validate the effectiveness of the proposed method. The proposed approach provides a design tool for more affordable and higher-performance structural materials.*

Again, I confirm that the manuscript is original, has not been submitted to any other journals, and is not under consideration elsewhere. I would be grateful if the revised manuscript could be reviewed again and be considered for publication in your prestige journal.

Sincerely yours,

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Details of point-by-point responses and revisions

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Reviewer #1 Comments:

The subject of the study is numerical analysis of bio-inspired porous structure. The conditions of the analysis carried out consisted of surface pressure loading of the structure and observation of its behavior. The study of the porous composite structure was inspired by the cuttlefish tail, while the main goal was to optimize its mechanical properties. The analysis was based on topology optimization, the schematic diagram of which is shown in Figure 1.

The subject of the research is described quite extensively, moreover, supported by relevant graphics, it forms a whole, thoroughly explaining the investigated models. The obtained conclusions are presented in a logical and coherent manner for the reader. The methodology of the research conducted, as well as the results and conclusions, are correctly stated, and the work itself is of high scientific value, however some parts of the proposed manuscript need improvement:

Figure 6 lacks a legend to correctly analyze the graphic

Authors' response:

The author really appreciates the reviewer for taking time reviewing my manuscript and providing valuable comments. The caption on Figure 7 (one addition figure was inserted before Figure 6, so the figure number was re-ordered) has revised as highlighted

"**Figure 7.** A partially assembled porous structure (a) formed by the topology-optimized periodic lattice blocks (4 cells in length, 4 cells in depth, and 3 cells in height) and. (b) fabricated by plastic (ABS) 3D printing (2 cells in length, 2 cells in depth, and 2 cells in height)."

The corresponding description in the text has revised as highlighted

"The partially assembled porous structure formed by the topology-optimized periodic lattice blocks is shown in Figure 7 (a), where the length is 4 cells, the depth is 4 cells, and the height is 3 cells. Comparing the cross-sectional structural profile of the cuttlefish bone, as shown in Figure 2, it is easy to find the structural similarity between the actual model and the topology-optimized model. The color plot on the partially assembled structure shows the vertical compressive stress distribution, with higher stress at the bottom of each pillar and lower stress at the upper of each cell. Figure 7(b) shows the physically assembled structure by 3D printing using plastic (ABS), with a length of 2 cells, a depth of 2 cells, and a height of 2 cells. The topology-optimized model was converted into a 3D digital model using SolidWork and then input into the 3D printer. The 3D printing process of such complex geometric structures is time-consuming."

Figure 7(b) of 3D printed model was added for responding to the other comment from the reviewer.

Reviewer #1 Comments:

Too short text referring to table 3. The table presented contains a large amount of data, no detailed reference of the studied structure to other materials. The current form looks as if table 3 is a filler of the article, this should be corrected.

Authors' response: Yes, the author totally agrees the comment by the reviewer, the role of Table 3 acts as a comparison and validation for the current work. The corresponding revision and explanation have been added to the paragraph as highlighted:

"To better evaluate the outcomes from this work and to validate the effectiveness of the current work, the current work is compared with the work from ref. [59] and the results are listed in Table 4 and plotted in the format of Ashby chart in Figure 8 [60]. Figure 8 provides a normalized platform for validating the current work by comparing some of the material properties related to density, porosity, matrix and reinforcement, Young's modulus, Poisson's ratio, and their specific properties relative to their density. The materials include the biomimetic designed and topology-optimized 3D lattice structural material (this work), many common bulk materials, and porous FRPCs. According to the research in ref. [59], the materials used to fabricate the samples are PLA and DiCFR PLA. The RVE models designed from the reference were based on the biomimetic inspiration without TO simulation, such as 2D hexagon model, 2D cuttlefish bone model, and 3D octahedron model. According to the relevant standard test methods for the tensile properties of polymer-based composites provided by the American Society for Testing and Materials (ASTM), the testing compressive loads were applied in the X, Y, or Z direction, respectively. The samples from the reference were prepared by 3D printing process, and as the DiCFRPLA composite filament used in 3D printing, the discontinuous fibers were mainly aligned along the printing path. Therefore, the printing direction is basically the fiber direction for the samples."

"From the data in the chart (Figure 8) and the research work in the reference, it was fond that the printing directions (also referring to the fiber directions) for DiCFRC, load types (referring to tension or compression), porosity (volumetric reduction) have great effects on the samples' stiffness (Young's modulus) and specific Young's modulus. it is also clear that the specific Young's moduli (E/ρ) of the 2D and 3D cuttlefish bone models are higher than or equivalent to that of the CFRPLA bulk composites. The 3D octahedron models may be optimized for better performance. However, this research shows the specific Young's modulus of the biomimetic inspired and TO lattice structures has much higher value, which validated the effectiveness of the current design approach for the lattice structural design and also explains why the cuttlefishes can withstand high pressure in deep sea."

Reviewer #1 Comments:

The analysis lacks several relevant literature items, making the literature review and conclusions more relevant e.g., the paragraph on porous structures (lines 72-77) reinforced with composite particles lacks a description of porous structures reinforced with silicon carbide particles (sample publications below)

DOI: 10.1016/j.compstruct.2022.116102; DOI: 10.12913/22998624/153028

Authors' response: Yes, the author totally agrees the comment by the reviewer. The corresponding revision and explanation have been added to the paragraph as highlighted

"Porous composites reinforced by discontinuous fibers (DiFs) offer great flexibility in tailoring specific physical properties by controlling the composition, the microstructures of the constituents, and the fiber orientation during fabrication. Periodic porous composites consist of many identical base blocks. Manipulating the phase distribution and fiber orientation in these base blocks provides an effective way to design multifunctional structural composites [22-26]. One of the intensive applications of the extensive research on porous composite structures is the development of thin-walled energy-absorbing components in the automotive industry. The structures and the materials (usually using aluminum for weight reduction with relative strength) are modified for passenger safety. Initially, additional walls were used inside the thin-walled profile, which increased the energy absorption efficiency and the peak value of the crushing force. Another solution to increase energy absorption is to fill the thin-walled profile with a honeycomb structure. However, it increases cost and weight, especially for the honeycomb structures with much thinner walls, and the improvement in energy absorption is limited. Engineers then began to strengthen the structures by filling the interior with lightweight syntactic foams, such as aluminum-silicon carbide syntactic foams [27, 28]. The main advantages of such syntactic foams are the ease of filling adaptation to the shape of the thin-walled structures and the possibility change the mechanical properties by using balls of different matrix materials of different thicknesses as lightweight porous fillings. In addition, aluminum-ceramic composite foams are widely used as thermal or sound insulation, multifunctional structural materials, in the shipping industry."

In addition, two more references have been added in the appropriate place as reference number [27] and [28], the rest of the references have been reordered

27. Rogala, M.; Tuchowski, W.; Czarnecka-Komorowska, D.; Gawdzińska, K. Analysis and assessment of aluminum and aluminum-ceramic foam structure. Advances in Science and Technology Research Journal

2022, 16(4), pp. 187-197.

28. Rogala, M.; Gajewski, J, Gawdzińska, K. Crashworthness analysis of thin-walled aluminum columns filled with aluminum-silicon carbide composite foam. Composite Structures 2022, 299, 116102 (14 pages).

Reviewer #2 Comments:

This manuscript presents a biomimetic lattice design inspired by cuttlefish bone. A topological optimization using computer modeling was performed to explore the best solution with minimized structural compliance and maximized structural stiffness for 3D periodic discontinuous carbon fiber-reinforced nylon lattice blocks. The mechanical properties of the topologically optimized lattice structures were characterized by computer modeling and were compared with previously reported similar designs, demonstrating the effectiveness of the proposed approach.

This manuscript shows good organization but falls short of clarity and rigor. I do not recommend this manuscript for publication before the author could consider the following questions and revise the manuscript. Detailed comments are listed below.

1. In general, I have no doubt about the section arrangement. However, there is an unacceptable skip between the display of biological cuttlefish bone (Fig 2) and the topologically optimized design (Fig 4). It is unclear how the author reaches the design in Fig 4 from the initial block structure. Since there is a number of iterations, it is better to demonstrate how these iterations provide us with gradually improved structures using an extra figure.

Authors' response:

The author really appreciates the reviewer for taking time reviewing my manuscript and providing valuable comments. The corresponding revision and explanation have been added to the paragraph as highlighted and additional figure (Figure 4) was added before the previous Figure 4, and the rest of the figures were re-ordered.

"The ANSYS TO module was used to perform TO of various porosities (material volume reduction) on the periodic lattice blocks with an orthotropic material, such as DiC FRPC. The TO domain can be controlled by customizing regions to be optimized and non-optimized by predefined bottom layer and the top layer considered as non-optimized regions. During the OT process, the objective function (structural compliance) decreases as the number of iterations increases, and after a certain number of iterations, the iterative results finally converge to a stable minimum value, indicating that the structural rigidity reaches its maximum value, and the complex optimized topology is realized. Figure 4 shows that the material on the front of the lattice block represents the progressive iterative modeling process from the beginning to the end of the TO process, where the red color (at the right end of the color bar) represents 100 vol.% material/solid, while the dark blue color (at the left end of the color bar) represents 0 vol.% material/void. It can be seen that the TO modeling iterative process is rapidly approaching the convergence state, and after the entire TO process reaches 40%, the modeling results are very similar to those at the end of the TO process. Figure 5 shows a complex topology-optimized lattice block with 90% porosity (90% material volume reduction) of the initial 3D periodic block. The surface profile shown in the figure was smoothed based on the surface profile represented by the elements using SolidWorks, a 3D solid modeling computer-aided design and computer-aided engineering software. Comparing the optimized block with the smaller cuttlefish bone unit-cell structures having the similar porosity, referring to Figure 2, the two structural topologies look similar."

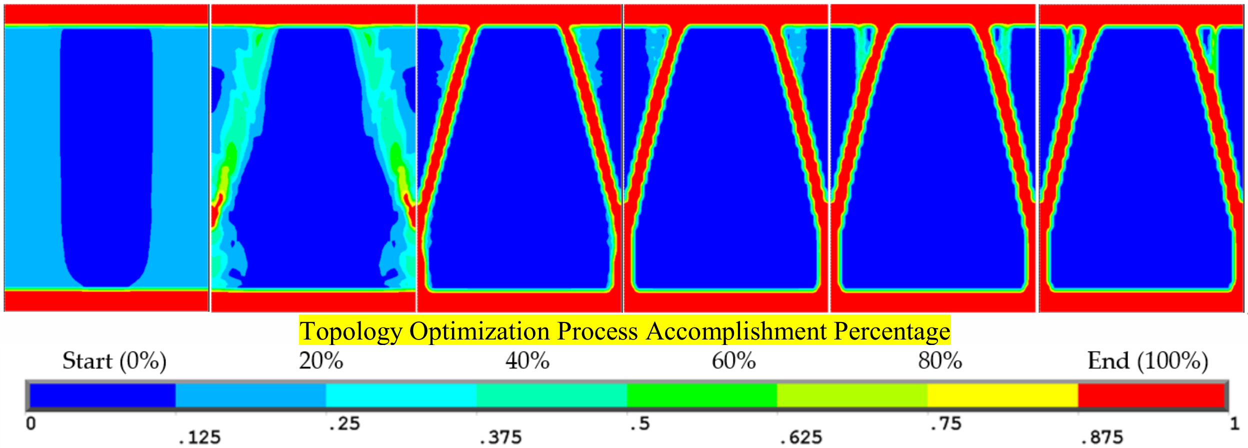


Figure 4. The progressive material representation of the lattice block front face through the TO process.

Reviewer #2 Comments:

2. Mesh convergence study was conducted to decide on a mesh size of 0.03 um in the actual study. It should be double-checked whether this number is correct, given the minimum displayed mesh size as 4 um in Table 2. Moreover, in addition to evaluating the influence of mesh size on maximum displacement, I would like to see how it affects the mechanical properties the author currently presents in Fig 5. It is more convincing if the mechanical properties converge as the mesh size gets smaller.

Authors' response: Yes, the author totally agrees the comment by the reviewer. The corresponding revision and explanation have been added to the paragraph as highlighted

"After achieving the topology-optimized lattice block structures for various porosities, the mechanical properties of the topology-optimized periodic lattice blocks should be characterized. As a case study, compression tests were carried out through FEA modeling using ANSYS software. The applied loads, the boundary conditions, and the constraints are similar to the mesh convergence tests, referring to Figure 3. A pressure was applied on the top surface (Z = height) of the optimized lattice block. The bottom surface (Z = 0 and $U_Z = 0$), the back face (X = 0 and $U_X = 0$), and the left face (Y = 0 and $U_Y = 0$) are set as symmetric faces. The front face (X = depth and the displacements in the X-direction are the same for the entire face) and the right face (Y = width and the displacements in the Y-direction are the same for the entire face) are set as periodic faces. Before material property characterization by FEA modeling, for each lattice block model with a specific porosity, a mesh convergence study was first carried out to determine the appropriate mesh size. Table 3 lists the mesh convergence study data for the 90% porosity topology-optimized lattice block model, in which the maximum displacement and Young's modulus were recorded and extracted for mesh determination criteria. Since the models are topologically irregular, meshing the model with hexahedral elements would cause algorithmic difficulties, therefore, the tetrahedral elements were used. After mesh convergence study, the 90% porosity lattice block model and other porosity lattice block models all adopted a mesh size of 3 μm, which is consistent with the mesh size used in the initial lattice block model. Since the maximum stress is usually induced at the edges or corners or notches of the model and is very sensitive to the mesh size, it is generally not recommended as a criterion for mesh convergence studies. The different specific Young's moduli in the Z-direction (fiber-direction) versus the porosity of the topology-optimized lattice blocks are shown in Figure 6. It can be seen that these relationships are generally not a monotonically changing pattern (monotonically increasing or monotonically decreasing). There may be an inflection point where the material performance (properties) is at a maximum or minimum point, which can be adequately accounted for when effectively designing novel material lattice blocks."

In Table 2, the data for mesh size of 3 um has been added and Table 3 has been added for mesh size study of the topology-optimized lattice block model and the rest of the table has been re-ordered.

Table 3. Mesh convergence study of the 90% porosity topology-optimized lattice block under a pressure on the top surface with a periodic boundary constraints and symmetric boundary conditions.

Mesh Size	Total	Total Nodes	Maximum	Young's Modulus

(μm)	Elements		Displacement (μm)	(GPa)
10	85097	129527	9.1033	1.0471
5	124364	185968	9.1781	1.0716
4	137916	206287	9.1815	1.0732
3	183201	273919	9.1904	1.0732

Reviewer #2 Comments:

3. Fig 6: what is its dimensional/mechanical/structural information?

Authors' response: Yes, the author totally agrees the comment by the reviewer. The corresponding revision regarding the dimension of the model and explanation have been added to the paragraph as highlighted and the material properties are listed in Table 1.

"Before TO calculation, selecting an initial lattice block and setting initial constraints and boundary conditions according to the biomimetics are critical steps in the design. After carefully observing the transverse cross-sectional profile of the cuttlefish bone and its conditions during the millennium evolution, as shown in Figure 2, it was found that for the smaller cuttlefish bone samples with a macroscopic length of about 100mm, the microstructural lamella spacing is around 100-200 μm in height and pillar spacing is around 80-100 μm in width, which results in lattice blocks with possible aspect ratios between 1 and 2.5. Therefore, an initial 3D periodic block was designed, as shown in Figure 3. In the model, the height is 150 μm, both width and depth are 100 μm, and the ratio of height to width and depth (H:W:D) of 1.5:1:1 was chosen. The top surface is subjected to a pressure of up to 6 MPa, which is associated with the most extreme pressure experienced by the cuttlefish under the deep water. The non-topology optimization layer thickness is 8 μm. The sides and corners of the bottom face were constrained, so when the periodic boundary conditions were applied, the periodic block must always uniformly expand laterally during compressive deformation. The elements in the top and bottom layers in grey were not subjected to TO. The initial orientations of the DiCFs in the model were vertically aligned. "

Reviewer #2 Comments:

4. The visualization of table 3 is not satisfactory. In addition to the ambiguous difference between the last two rows, it is better to use an Ashby chart plot to replace table 3, like Fig 4 in the following paper: **Zheng, Xiaoyu, et al. "Ultralight, ultrastiff mechanical metamaterials." Science 344.6190 (2014): 1373-1377**.

Authors' response: Yes, the author totally agrees the comment by the reviewer. The corresponding revision regarding the Ashby chart plot has been added as Figure 8 (a) and (b), in addition to replace Table 4. The corresponding revision and explanation has been added accordingly as highlighted as following

"To better evaluate the outcomes from this work and to validate the effectiveness of the current work, the current work is compared with the work from ref. [59] and the results are listed in Table 4 and plotted in the format of Ashby chart in Figure 8 [60]. Figure 8 provides a normalized platform for validating the current work by comparing some of the material properties related to density, porosity, matrix and reinforcement, Young's modulus, Poisson's ratio, and their specific properties relative to their density. The materials include the biomimetic designed and topology-optimized 3D lattice structural material (this work), many common bulk materials, and porous FRPCs. According to the research in ref. [59], the materials used to fabricate the samples are PLA and DiCFR PLA. The RVE models designed from the reference were based on the biomimetic inspiration without TO simulation, such as 2D hexagon model, 2D cuttlefish bone model, and 3D octahedron model. According to the relevant standard test methods for the tensile properties of polymer-based composites provided by the American Society for Testing and Materials (ASTM), the testing compressive loads were applied in the X, Y, or Z direction, respectively. The samples from the reference were prepared by 3D printing process, and as the DiCFRPLA composite filament used in 3D printing, the discontinuous fibers were mainly aligned along the printing path. Therefore, the printing direction is basically the fiber direction for the samples. ”

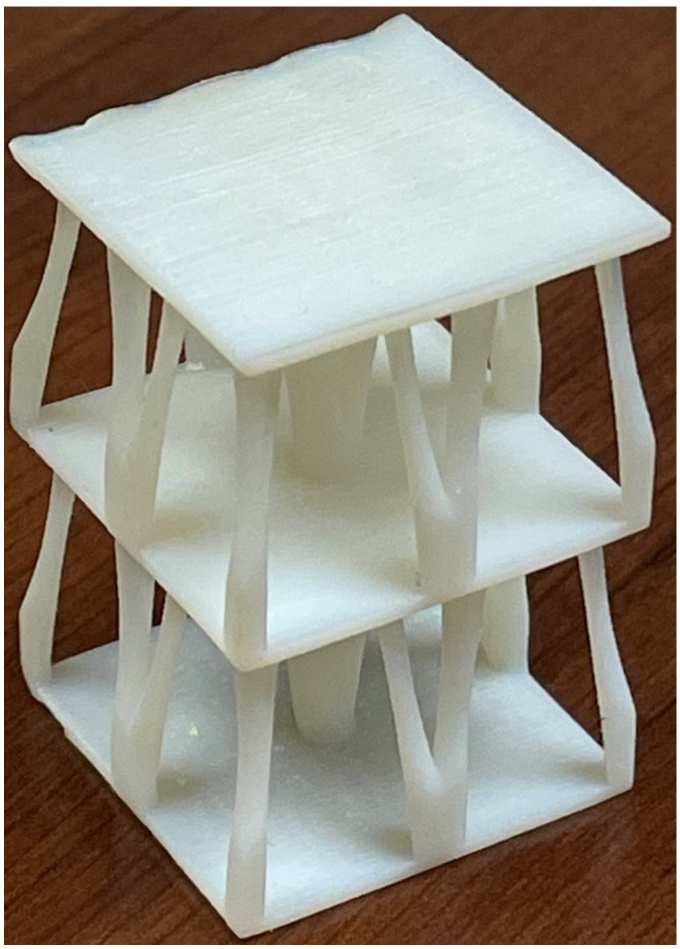
One additional reference has been added ad following

60. Zhang, X.; Lee, H.; Weisgraber, T.H.; Shusteff, M.; Deotte, J.; Duoss, E.B.; Kuntz, J.D.; Biener, M.M.; Ge, Q.; Jackson, J.A.; Kucheyev, S.O.; Fang, N.X.; Spadaccini, C.M. Ultra-light, ultra-stiff mechanical metamaterials. Science 2014, 344(6190), pp. 1373-1377.

Reviewer #2 Comments:

5. Mechanical property characterizations were only performed using FEA, which is not following the flowchart in Fig 1. Experiments are essential to examining the FEA results. Why did the author not conduct 3D printing and experiments?

Authors' response: Yes, the author totally agrees the comment by the reviewer. The author has tried 3D printing for the assembled structure based on the topology-optimized lattice blocks using ABS material. However, since the structure is irregular and extremely time consuming for 3D printing. Since there was not enough funding support, the 3D printing using the actual material (DiCFRPC) and the experiments have been canceled. The image of the 3D printing partial assembled structure using ABS has been added as the Figure 7(b) as following.



(b)

Figure 7. A partially assembled porous structure (a) formed by the topology-optimized periodic lattice blocks (4 cells in length, 4 cells in depth, and 3 cells in height) and. (b) fabricated by plastic (ABS) 3D printing (2 cells in length, 2 cells in depth, and 2 cells in height).

Dear Editor: FYI, in addition to the above responses to the reviewers’ comments, the author has gone over the entire text and rewritten many sentences accordingly.