Title:
Material and Structural Design based on Biological Information using Optimized Stress Distribution

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Introduction:
Creatures have acquired efficient structures for their survival and propagation through their evolution. Such efficient structures in nature have been analyzed and exploited to solve a variety of engineering problems [1]. This solution is called bio-inspired design, also known as biomimetic design, and its ability attracts much attention recently. For the best use of efficient features in nature, further cooperation between engineering field and biology field is desired. In recent years, mimicking biological material surface characteristics has become active as nanotechnology advances [2]. However, there is little case that extracts and applies biological material features for designing industrial material or structure.

General biomimetic design utilizes specific features of a creature for a specific product. There is a one-to-one relationship between the creature and the product in conventional methods, and such a relationship is difficult to apply to other cases. Thus, in this study, by adopting a modeling process for the conventional biomimetic method, a framework that can utilize arbitrary biological information is presented.

Biological material:
To establish the proposed method, a lightweight layered material based on the exoskeleton of the American lobster was designed. The exoskeleton of a lobster combines high mechanical strength with minimum material use and it has a characteristic fiber-based structure [3]. We focused on its potential applicability to the design of lightweight fiber-based mechanical structures and analyzed it by performing material tests and FE simulations.

Material tests
The larger chela (the crusher) was focused on as a characteristic functional unit of the American lobster, and compression tests were performed on specimens taken from the crusher. First, FE models were developed to simulate the flow of forces during predation and those caused by external impact. Through these simulations, the relationships between the results of material tests and the functions of each part of the chela were revealed [4]. By considering the results of the simulations, the locations of specimens and the directions in which they were cut out were determined. The cut specimens were fixed between metal plates and compression tests were performed on them.

FE modeling
Half of a crusher without the dactyl (the part moved by a muscle) was modeled by CAD (Fig. 1), and a force was loaded in the y direction to imitate the pinching of prey and impacts from external factors. To model predation, the loading point was in the middle section of the teeth since lobsters invariably attempt to crush their prey near this point. In accordance with the relationship between the output force

and the chela height [5], the loading force was set to 54 N, which was considered to be a realistic value. On the other hand, to model an external load, the loading point was on the upper edge of the

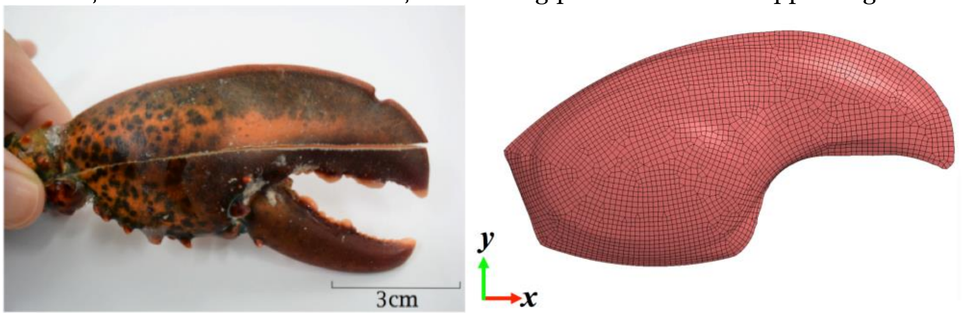

Fig. 1: (a) Crusher chela of American lobster and (b) digital model of the crusher [4].

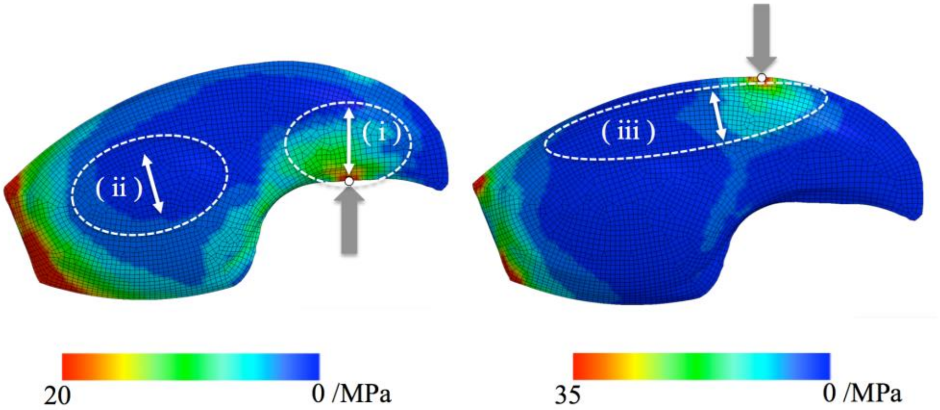

Fig. 2: Contour maps of Mises stress in loading simulation. (a) Predation and (b) external impact.

chela and the loading force was set to 64 N. To form a compatible half model, some restrictions were added. The circumference of the model was restricted to prevent displacement in the z direction and rotation around the x and y axes. The boundary of the body side was restricted to prevent displacement in the x, y and z directions and rotation around the y and z axes. Fig. 2 shows contour maps of the Mises stress obtained from the loading simulation. The loading point is indicated by the white dot and the gray arrow indicates the loading direction. According to Fig. 3, strong stress occurred near the loading point, while the center part of the model exhibited relatively low stress. Considering the flow of the forces, three sections were chosen in which to prepare specimens: (i) the tip, (ii) the center part, and (iii) the edge. In each section, the stress flow direction was defined as shown in Fig. 3 with white arrows, and specimens were prepared whose loading direction was parallel or transverse to the defined stress directions. As a result of this simulation to decide the locations and directions of the specimens, we were able to perform material tests that took account of the original functions of the bionic model. In this paper, the behaviors observed in the compression tests are treated as representative material properties and the results are compared to extract differences between different sections.

<u>Proposed method and application result:</u>

Outline of the proposed method

Here, our proposed method is briefly explained. First, a creature that may provide inspiration for the design of industrial materials is selected. Next, material tests are conducted on specimens taken from the creature. In this phase, observations on the structure are also conducted. Through these experiments and observations, the mechanical properties of the biological material are revealed. Then, FE models of the biological material are created on the basis of the experimental results. Here, some indeterminate material parameters are identified by inverse analyses, and material models that exhibit the same deformation behavior as the actual biological material can be obtained. Through this

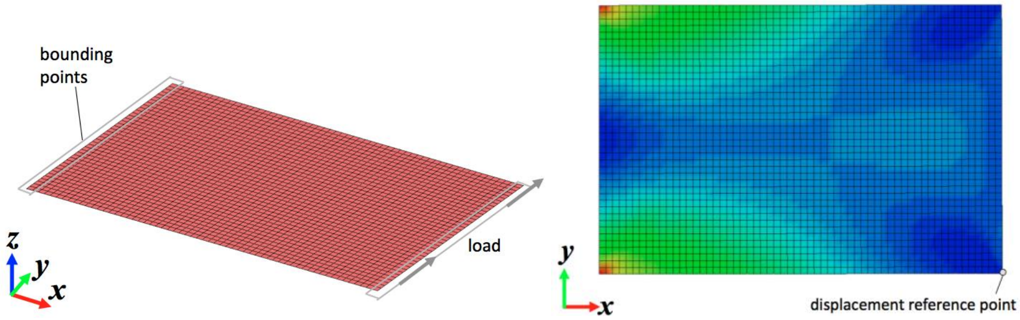

Fig. 3: (a) Boundary conditions and (b) Mises stress counter map of initial model.

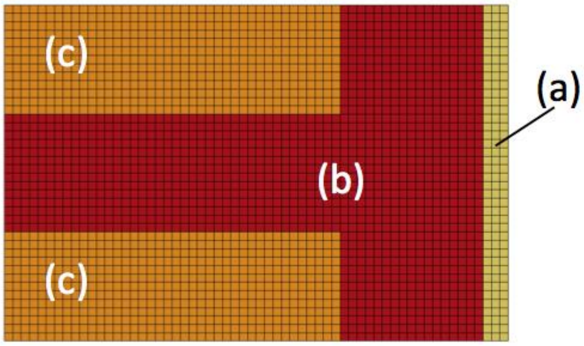

Fig. 4: Divided model for the proposed method.

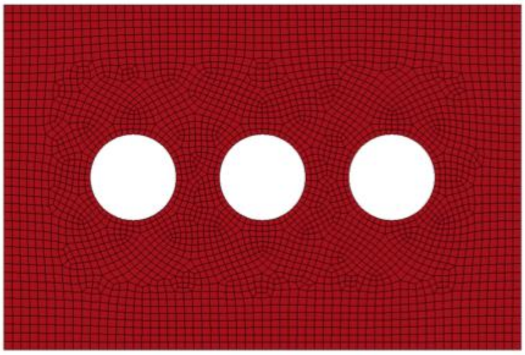

Fig. 5: Perforated model for conventional method.

modeling process, the properties and structures of the biological material, which affect the functions of the material, are clarified. Thus, in the final phase, the features of the biological material are extracted by determining the relationship between the material functions and the material properties/structures. Through this flow, information on the biological material is extracted for use in the design of industrial materials. In the material design phase, the desired functions of the material are first decided. Then optimization is conducted on the basis of the data extracted by the proposed method. In this paper, as an example of the application of the proposed method, the design of a lightweight layered material based on the exoskeleton of the American lobster is demonstrated. The

Tab. 1: Initial model data and analysis result.

Mass /kg	Stress /MPa	Displacement /mm
2.57	143	0.619

Tab. 2: Analysis results of optimized model.

	mass /kg	stress /MPa	displacement /mm
Proposed method	1.96	100	1.02
Conventional method	2.00	111	0.994

American lobster exoskeleton combines high mechanical strength with minimum material use and its features may inspire the design of lightweight materials.

Optimization problem and results

We set up an optimization problem with the aim of designing a more lightweight layer structure. Fig. 3 shows a schematic representation of the initial model, which consists of an eight-layer shell made of material properties with some arbitrary initial values. The structure was bounded on one of its short sides and the other short side was loaded in the y direction. The results of analysis of the initial model, i.e., the mass of the model, the maximum Mises stress and the displacement at the reference point, are shown in Tab. 1. Using these data, to obtain a more lightweight model, optimization of the material and geometry was conducted by the proposed method and the conventional method. Three orthotropic materials, which differed in density and Young's modulus in the direction with greatest strength, were prepared assuming the mechanical properties of CFRP (carbon fiber reinforced plastic). The variables in this optimization problem are summarized in the selection of these materials and the setting of the model thickness. LS-OPT was used for the computational optimization.

In the proposed method, first, the initial model was divided in three parts by referring to the Mises stress contour map of the initial model. Fig. 4 shows the three parts, which require the functions of (a) avoiding stress concentration without too much displacement, (b) minimizing deformation to reducing displacement near loading points, (c) avoiding destruction by permitting deformation and reduce stress concentration. From a functional viewpoint, these three parts correspond to the tip, center and edge of the lobster's chelae, respectively. To meet these requirements, the material for each layer of the model was defined in three parts. The thicknesses of the parts were variables in this optimization; therefore, three variables existed.

On the other hand, the conventional method was conducted by modification of the geometry and computational optimization of the materials and thicknesses. A technique in structural design is to include some holes to reduce weight while maintaining sufficient strength. In this case, three holes were set as shown in Fig. 5, and the material in each layer and the thicknesses of the layers in the model were optimized by LS-OPT. In this case, a total of nine variables existed. Analysis results of the proposed method and conventional method are summarized in Table 2. Although the maximum displacement was slightly increased, mass and maximum stress reduction were successfully conducted.

Conclusion:

In this study, a material design method utilizing the elaborate mechanical features of creatures was proposed. The proposed method mainly consists of three phases: (i) obtaining mechanical properties by performing material tests and structure observation, (ii) making an FE model of the biological material based on the results of the material tests and (iii) extracting the mechanical features of the biological material in accordance with the relationships between material properties and biological functions. The proposed method was demonstrated in a design example in which an optimized structural design was searched through stress distribution, resulted in a good design satisfying both weight and strength demands.

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