Title:

Method for Evaluating Mechanical Characteristics of Biological Material for Bio-inspired Lightweight Design

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Introduction:

With increasing concern about cost reduction and environmental destruction, lightweight structural design is essential in the product design process. Lightweight design enables products to be made with the minimum amount of materials and their transport at a lower cost. Nowadays engineers can use structural and topological optimization to yield lightweight structures. Although these methods have been implemented in commercial software, there are some practical restrictions on design variables and conditions. For example, it is difficult to obtain the optimal shape and topology while simultaneously considering the anisotropy of materials. On the other hand there are many efficient and lightweight structures in nature that partially utilize material anisotropy. In this paper, an exoskeleton of the American lobster (*Homarus americanus*) have been adopted as a biological model of such structures and attempted to learn the mechanism of their lightweight design.

Bio-inspired design, also known as biomimetic design has emerged as a new solution to engineering problems these days. Through their evolution, creatures have acquired efficient structures for their survival and propagation. Such efficient structures in nature have been analyzed and exploited to solve a variety of engineering problems. In particular, exoskeleton of the American lobster has been analyzed as a natural fiber-based composite material that combines high mechanical strength with minimum material use [1, 2]. We focus on its potential applicability to the design of lightweight mechanical structures through analysis by material tests and FE simulations. Sachs et al. have previously developed tensile test method for the exoskeleton of the American lobster using specialized equipment [3]. In reference to this method, we construct a methodology for testing biological materials using plastic clamps made by a 3D printer. We also produced finite element (FE) models that simulate the predation action of lobsters which we comprehensively analyze by comparison with experimental results, from which we extracted some rules for the design of efficient and lightweight structures. Finally, we show an example of bio-inspired material design using features extracted from a biological model and construct an efficient lightweight structure.

Main Idea:

In this section we describe how to extract features from the biological model, and apply them for material design. First, we made FE models to simulate the flow of forces during predation. Considering the result of the simulations, we determined the location and direction for cutting out specimens. The cut specimens were mounted on plastic clamps made by a 3D printer and tensile tests were performed on them. Finally, we show an example of bio-inspired material design using features extracted from a biological model and construct an efficient lightweight structure.

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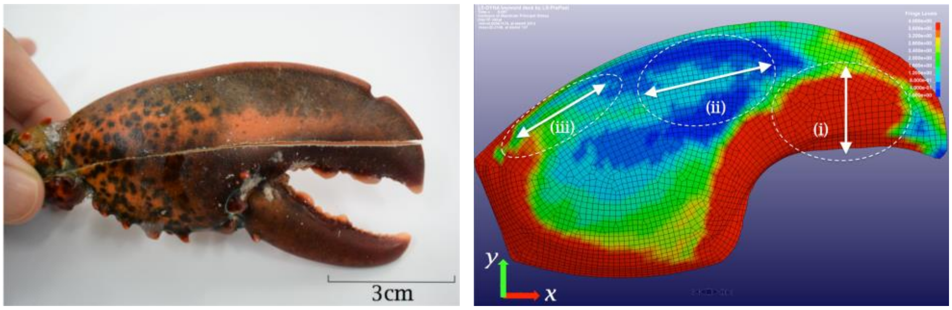

Fig. 1: (a) Crusher chela of American lobster and (b) contour map of first-principles stress in loading simulation.

FE modeling

Half of a crusher without the dactyl (the part moved by a muscle) was modeled by CAD, and a force was loaded in the *y* direction at the middle point of the teeth to imitate the pinching of prey. Fig. 1(b) shows a contour map of the first-principles stress obtained from the loading simulation. According to the map, strong stress occurred near the loading point while the center part of the model exhibited relatively low stress. In more detail, it shows particularly high stress along the upper edge of the model. Considering the flow of forces, we chose three sections in which to prepare specimens: (i) the tip part, (ii) the center part, and (iii) the edge part. In each section, we defined the stress direction as shown in Fig. 1(b) with white arrows, and prepared specimens whose longitudinal direction was parallel or transverse to the stress direction.

Tensile test

The specimens used for tensile tests were taken from the crushers of two American lobsters. The samples were cut into rectangular shape of approximately 15 mm length and 5 mm width, and the center part was narrowed to form bone-shaped test specimens as shown in Fig. 2(a). Then the waxy surface at both ends was abraded with a file to avoid slipping. To prevent the specimens from being subjected to unwanted loading during the preparation of the tensile tests, we made plastic clamps (Fig. 2(b)) with a shallow indent into which instant glue was poured to hold the specimens without extra loading. Processed specimens were stored at a low temperature in a humid atmosphere until testing to prevent their desiccation.

The experimental setup of the tensile tests is shown in Fig. 2(c). The maximum capacity of the load cell was 200 N and the electric cylinder moves to the left at a speed of 0.5 mm/s. By measuring the load and stroke until fracture, we were able to observe the stress-strain behavior of each specimen. We also recorded the tests on video so that we could review the behaviors of the specimens during the test and at the moment of fracture.

Result

Through the tensile tests, we obtained the material properties of the specimens, specifically the Young's modulus and fracture stress of the exoskeleton from the crusher chela of the American lobsters. As shown by the nominal stress-strain curves (Fig. 3), most of the specimens exhibited elastic deformation.

The specimens from the tip part of the crusher have a relatively low Young's modulus. Comparing the results for the two directions, we can observe material anisotropy: the specimens cut parallel to the stress direction have a lower Young's modulus and fracture stress. We also found that the thickness of the exoskeleton near the tip section was much greater than elsewhere. From the results for tip part, we suggest the following two features for the optimal functionality of lobsters.

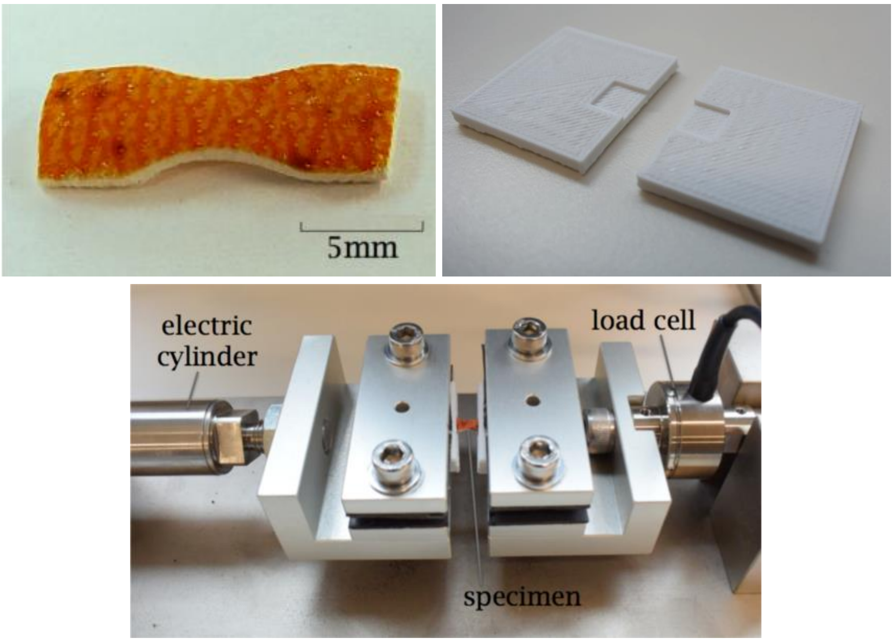

Fig. 2: Tensile tests preparation. (a) Bone-shaped specimen, (b) plastic clamps, and (c) experimental setup.

- **Feature 1**: They absorb a large amount of energy by decreasing the Young's modulus of the exoskeleton, especially parallel to the stress direction, and deforming its geometry.
- **Feature 2**: Their strength is increased by increasing the thickness of the exoskeleton.

Specimens taken from the center part had intermediate material properties, with the Young's modulus and fracture stress between those of the other parts. Thus, this part seems to be a transitional zone between the tip part and the edge part. There is no significant anisotropy in this zone, resulting in loaded stress being dispersed equally in all directions. The feature extracted for center part is as follows.

- **Feature 3**: Sections that are loaded with low stress have no anisotropy.

The Young's modulus and fracture stress of the specimens taken from the edge part were much higher than those taken from the other parts. The edge part corresponds to a morphologically sharp section; thus, it should have higher mechanical strength than the other parts. In addition, for male lobsters, a strong edge part is essential for encounters with other males. During antagonistic encounters, physical contact such as claw locking or pushing occurs frequently. To withstand sudden strong impacts without breaking, the exoskeleton of this part is expected to have evolved the following feature.

- **Feature 4**: Sections expected to be subjected to impact possess a higher Young's modulus and fracture stress.

By analyzing the results of the tensile tests, we obtained the above four features of a high-performance structure with minimum material use. In the next section, an example of material design that uses these efficient features is given.

Material design

Utilizing the four extracted features, we performed material design for a simple hook geometry using LS-DYNA software. The purpose of this optimization is to design a lightweight and durable structure similar to the exoskeleton of the American lobster. By connecting the lobster's features with each part of the hook model, we assign various material properties that assist stress dispersion. Finally we compare the behaviors with a standard model by FEM simulation.

First, we prepared an FE shell model consisting of seven parts made of isotropic material: MID1. Fig. 4(a) shows a contour map of the first principles stress when a load is applied at the red point in the direction of the red arrow. From the obtained flow of forces, we defined three types of sections: (i) high-stress sections, (ii) low-stress sections, and (iii) sections where strong impact occurs, associated with the lobster's features. These sections correspond to the tip, center, and edge parts of the lobster's crusher respectively. For each part of the FE shell model, the features that we extracted from lobsters should be the optimal strategy to disperse a large stress.

Subsequently, we defined two types of modified material properties for a materially optimized new model. The material MID2 is strongly anisotropic with the same Young's modulus as the original material in one direction but lower Young's modulus in the other two directions. It is also considerably lighter than the original material. MID3 is a weak and isotropic material with a much lower density and much lower Young's modulus than the original material. In accordance with the features extracted from the lobsters, we assigned these materials and modified the thicknesses for the new model.

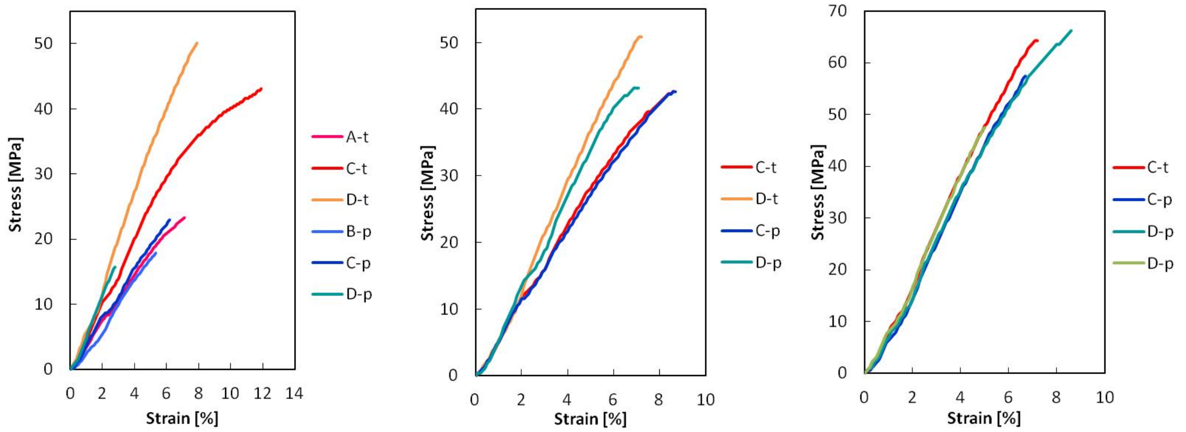

Fig. 3: Nominal stress-strain curves of (a) tip, (b) center, and (c) edge parts.
(A, B, C, D: individual; p: parallel direction; t: transverse direction)

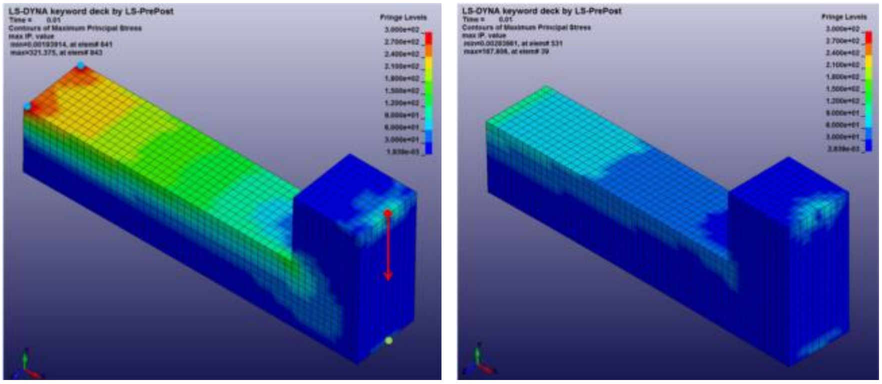

Fig. 4: Contour maps of first-principles stress: (a) Original model showing loading, stress, and displacement point. (b) Materially optimized model.

Finally, we performed a loading simulation for the original model and the optimized model. A load was applied to the red point shown in Fig. 4(a), and the maximum stress at the blue points and the maximum displacement at the green point were recorded. Fig. 4 shows the results of the simulation. The maximum stress of the optimized model was reduced to approximately half and the total mass was reduced by 11.3 %. Although the maximum displacement was increased in return for the dispersion of stress, the purpose of this example is to demonstrate a lightweight and durable structure, and little increase in displacement does not essentially affect the function as a hook. Thus, it appears to be important in bio-inspired product design to select an appropriate product with a similar purpose of the bionic models.

Conclusions:

In this paper we reported a method of extracting useful features from the lightweight structural design found in the American lobster. We performed tensile tests on specimens cut from the crusher chela of lobsters using plastic clamps made by a 3D printer. Through the tensile tests and analysis, we found that the crusher has a material strategy of decreasing stress while permitting deformation. Applying this feature, we formed a materially efficient and durable structure and confirmed the usability of features found in a bionic model in the material design process. As future work, combining this material design process with topological optimization may further increase the efficiency of structural design by considering both the material and the geometry simultaneously.

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