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Method for evaluating mechanical characteristics of biological material for bio-inspired lightweight design

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ABSTRACT
With increasing concern about cost reduction and environmental destruction, lightweight structural design is essential in the product design process. As a means of yielding products with more lightweight and efficient structures, in this paper a method of extracting useful features from a biological lightweight structure, that of the American lobster is proposed. Tensile tests were conducted on biological specimens using plastic clamps made by a 3D printer and clarified some rules for the design of lightweight and efficient structures. Using the rules of material design, a novel method for acquiring bio-inspired lightweight designs was proposed and its feasibility was shown by FEM simulation.

KEYWORDS
Bio-inspired design; lightweight design; 3D printing; FEM simulation

1. Introduction

In recent years, lightweight structural design has been desired for many types of industrial products. Lightweight design enables products to be made with the minimum amount of materials and their transport at a lower cost. Thus, producing products with the minimum weight while maintaining their functions is the ultimate goal for most R&D sections, especially in the automotive and aerospace industries [10]. Generally, to achieve this aim, engineers have proceeded on the basis of their experience and the previous designs. In the last two or three decades, the finite element method (FEM) has become an indispensable engineering tool in the design field. However, finite element (FE) analyses have not necessarily been effective since they yield deformation results rather than solutions. 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. Therefore, a new methodology should be created to design highly efficient lightweight structures, with the methodology itself based on laws of nature, namely, biological mechanisms. We thus focused on bio-inspired design, also known as biomimetic design, as a new solution to engineering problems. 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 [3]. From the viewpoint of lightweight design, Maier et al. proposed a method for abstracting the features of natural microstructures such as diatoms for use in topological optimization [6]. Zhao et al. developed a method of dead-load reduction and performance improvement for mechanical structures using the features of analogical samples in nature [11].

In this paper, the exoskeleton of the American lobster (*Homarus americanus*) have been adopted as a biological model of lightweight structures and attempted to learn the mechanism of lightweight design from them. The exoskeleton of the American lobster has been analyzed as a natural fiber-based composite material that combines high mechanical strength with minimum material use [2, 7]. We focus on its potential applicability to the design of lightweight mechanical structures through analysis by material tests and FE simulations. To conduct meaningful FE simulations on biological structures, sufficient information about them is required. However, little material data are available. Therefore, it is necessary to construct a methodology for testing biological materials. Sachs et al. have previously developed tensile test method for the exoskeleton of the American lobster using specialized equipment [8].

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As reported in this paper, because one of the difficulties of dealing with natural materials is their individuality, tests on biomaterials are conducted using plastic clamps made by a 3D printer whose dimensions depended on those of the specimens. FE models were also produced that simulate the predation action of lobsters which were comprehensively analyzed by comparison with experimental results, from which we extracted some rules for the design of efficient and lightweight structures. Finally, an example of bio-inspired material design is shown using features extracted from a biological model and construct an efficient lightweight structure.

2. Biological model

The features of the American lobster have been revealed from the standpoints of material, morphology, and functionality in previous researches. In this section, we briefly describe its distinctive features and their applicability to a biomimetic approach.

2.1. Features of American lobster

First, the characteristics of the materials composing the lobster's cuticle, which forms its exoskeleton, are discussed. American lobsters use chitin and various proteins as the basic materials of their cuticle, and form a hierarchical microstructure. According to Fabritius et al. [2], their hierarchical organization starts at the molecular level with monomeric saccharide units, which form α-chitin chains. Upon wrapping with proteins, the chitin molecules form nanofibrils, which aggregate into chitin-protein fibers. Chitin-protein fibers form planar sheets, which are stacked into a twisted plywood structure with a gradually rotating fiber direction. This helicoidally arranged structure forms the three main layers of the cuticle, which are called the epicuticle, exocuticle, and endocuticle.

This sophisticated hierarchical structure exhibits anisotropy at different length scales. At the microscopic level, the chitin crystals in the nanofibrils have strong intrinsic anisotropy in their stiffness. These chitin fibers form unidirectional reinforced planes, and by superimposing them, the microscopic anisotropy is removed. However at this level a new, more structurally based anisotropy arises from the honeycomb structure of the material [9]. These anisotropies, which can be expressed by the combination of twisted plywood and honeycomb structures, result in a material with superior mechanical properties at a lower weight. This is why the American lobster is frequently considered as a model natural lightweight fiber composite.

The cuticle of the American lobster is also of interest and has been studied as a multifunctional material. The shell of the main body segments provides support and functions as a protective shield against predation. On the other hand, mandibles and other mouthparts have the functions of holding, cutting, and grinding food items. Moreover, the cuticle forms a number of other interesting parts such as the joints between skeletal elements and the optical lenses in the compound eyes [2]. This material, which has high functional versatility, leading to the design of novel bio-inspired materials and seamless composite structures. In industry, seamless structural design can lead to simple assembly and a more efficient manufacturing process. Learning the mechanism of natural efficient material designs is necessary for further development in industry.

Understanding the behavior of functional units such as claws is indispensable for discussing the macroscopic functions of the American lobster. They have large dimorphic chelae, a larger crusher chela and a slimmer cutter chela. The cutter chela serves to hold prey while the crusher chela cracks shells. Both chelae have evolved to carry out these roles: the crusher closes relatively slowly while applying large force whereas the cutter applies a small force but closes rapidly. Elner et al. [1] measured the forces delivered by crusher chelae using strain gauges and revealed that the maximum force generated increased with the chela height. Comparing the forces produced by the two types of chelae, a crusher provides a larger maximum force than a cutter of the same height. From this result, they concluded that the morphology of the chelae appears to be correlated to the forces produced and the predation behavior. This idea, which indicates a relationship between morphology and function of creatures, is important for our study. The mechanisms of the lightweight structural design found in the American lobster are revealed and clarified by multilateral analysis of their material, morphology, and functionality.

2.2. Biomimetic principles of American lobster

American lobsters have been known to have highly sophisticated and efficient natural structures for years, and recently they have also been considered as biomimetic models. As we described in the previous section, American lobsters have fibrous and hierarchical structures made of chitin and proteins. Reichert et al. [7] focused on their potential to provide guidelines for applications of fiber-reinforced polymers (FRPs) in architecture and exploited their "biomimetic principles" to design an ultra-lightweight pavilion using an FRP. They identified three biomimetic principles in lobsters: functional integration, heterogeneity, and anisotropy. On the basis of these principles, they designed digital models for robotic fabrication processes and made a full-size architectural prototype.

In this paper, the elaborate mechanism of lightweight structural design is extracted from the bionic model of the American lobster. Their highly developed efficient structures suggest solutions for lightweight designs that follow natural optimized principles. When we exploit biological features for mechanical design, it is necessary to not only partially mimic nature but also comprehend the internal mechanism of a natural system, since its optimality is reproduced as a result of all its elements. To obtain a deeper understanding of a natural optimized mechanism, it is essential to analyze the target from a multifaceted viewpoint. We approach the optimality of American lobsters by considering their mechanical material properties, global morphology, and the functions of the units. Through such analyses, their lightweight structural mechanisms were extracted and they were applied to a specific example of material design for lightweight products.

3. Experimental method

The larger chela, the crusher, was focused as a characteristic functional unit of the American lobster and performed tensile tests on specimens taken from the crusher. First, FE models were made to simulate the flow of forces during predation. Considering the result of the simulations, the location and direction for cutting out specimens were determined. The cut specimens were mounted on plastic clamps made by a 3D printer and tensile tests were performed on them.

3.1. 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. 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 [1], the loading force was set to 54 N, which was considered to be a realistic value. To form a compatible half model, some restrictions were added. The circumference of the model was restricted not to displace in the *z* direction and not to rotate around the *x* and *y* directions. The boundary of body side was restricted not to displace in the *x*, *y*, and *z* directions and not to rotate around the *y* and *z* direction.

Fig. 2 shows a contour map of the first-principles stress obtained from the loading simulation. According to Fig. 2(a), strong stress occurred near the loading point while the center part of the model exhibited relatively low

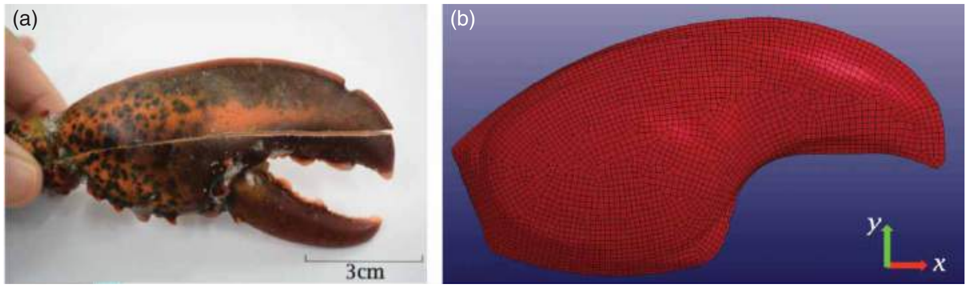

Figure 1. (a) Crusher chela of American lobster and (b) digital model of the crusher.

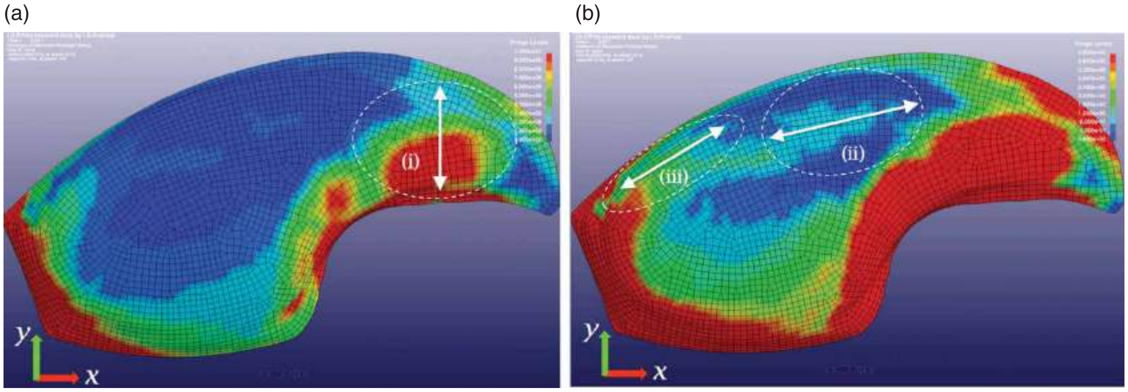

Figure 2. Contour maps of first-principles stress in loading simulation with range of (a) 0–10 and (b) 0–5 MPa.

stress. In more detail, Fig. 2(b) shows particularly high stress along the upper edge of the model. Considering the flow of forces, three sections were chosen in which to prepare specimens: (i) the tip part, (ii) the center part, and (iii) the edge part. In each section, the stress direction was defined as shown in Fig. 2 with white arrows, and prepared specimens whose longitudinal direction was parallel or transverse to the stress direction. 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, behaviors for tensile tests are treated as representative material properties and results are compared each other to extract difference between sections.

3.2. Sample preparation and tensile tests

The specimens used for tensile tests were taken from the crushers of two American lobsters. The front and back sides of the same crusher were treated as different samples since there was a visually recognizable difference between them; the front sides had black spots over a large area. 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. 3(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, plastic clamps (Fig. 3(b)) were made that have a shallow indent into which instant glue was poured to hold the specimens without extra loading. The thickness of the specimens varied from approximately 0.5 to 1.2 mm depending on the location, thus, we formed indents with three different depths and selected the most suitable one for each specimen. An indent that was too deep for the specimen caused slipping, while too a shallow indent led to the destruction of the specimen in the setting of the tensile tests. By carefully choosing the most suitable depth of the indent for the different specimens, it is able to transmit accurate loads to the specimens during the tests. The deformation of the plastic clamps in the test was also considered and concluded that the strain on the specimens was increased slightly but negligible effect on the stress when using the clamps. Since our aim was only to roughly compare the stress-strain behavior rather than obtain values of stress and strain with high accuracy, the deformation of the plastic clamps was ignored in this study. 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. 4. 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, it is able to observe the stress-strain behavior of each specimen. The tests were also recorded on video so that we could review the behaviors of the specimens during the test and at the moment of fracture.

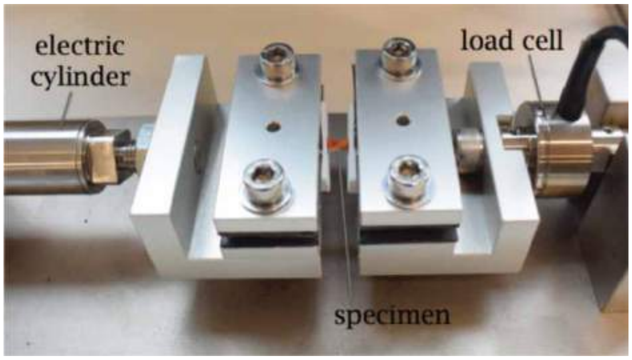

Figure 4. Experimental setup of tensile tests.

4. Results

Through the tensile tests, the material properties of the specimens were obtained, 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. 5), most of the specimens

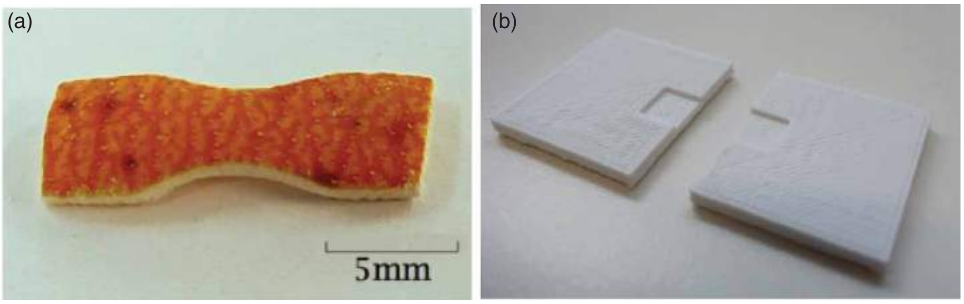

Figure 3. Sample preparation. (a) Bone-shaped specimen and (b) plastic clamps.

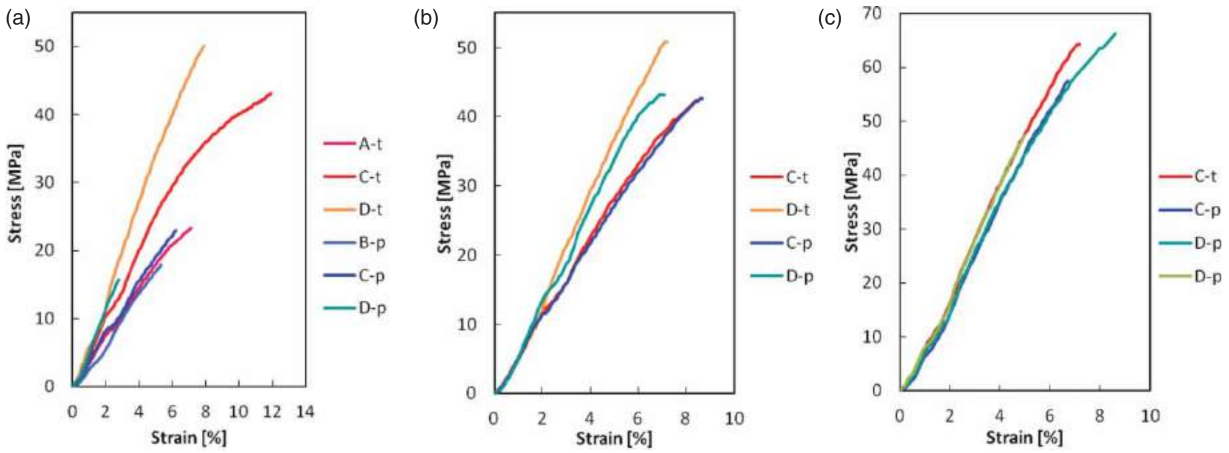

Figure 5. Nominal stress-strain curves of (a) tip, (b) center, and (c) edge parts. (A, B, C, D: individual; p: parallel direction; t: transverse direction)

Table 1. Number of samples, average Young's modulus, and fracture stress. (p: parallel to the stress direction, t: transverse to the stress direction)

	tip (p)	tip (t)	center (p)	center (t)	edge (p)	edge (t)
number of samples	3	3	2	2	3	1
Young's modulus [MPa]	422	477	590	630	875	932
fracture stress [MPa]	18.8	38.8	42.9	46.8	57.0	64.3

exhibited elastic deformation. Tab. 1 shows the average Young's modulus and fracture stress of the specimens, which are classified into the part and direction. In this section, the results and the information obtained from them were explained in detail.

4.1. Tip part

As shown in Tab. 1, the specimens from the tip part of the crusher have a relatively low Young's modulus. Comparing the results for the two directions, material anisotropy was observed: the specimens cut parallel to the stress direction have a lower Young's modulus and fracture stress. It was found that the thickness of the exoskeleton near the tip section was much greater than elsewhere. From the results for this section, the following two features were suggested for the optimal functionality of lobsters.

- **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.

According to the results of the simulation performed before the tensile tests, the tip part is subjected to the greatest loading when lobsters pinch their prey. It is of great importance that the crusher does not break. Thus, it is consider that lobsters have evolved so that their exoskeleton is relatively elastic near the loading section, allowing a large stress to be distributed through deformation. The fracture stress of the specimens in the parallel direction appears to be quite small; thus, it is suspected that excessive stress concentration caused by a difference in the thickness in individual specimens (i.e., 0.6 mm on the left side and 1.2 mm on the right side), which is a characteristic of the specimens taken from the tip and cut in the parallel direction.

4.2. Center part

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 this part is as follows.

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

4.3. Edge part

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. Overall, it appears that the exoskeleton of the American lobster's crusher chela has a material strategy of decreasing stress through deformation. For the action of predation, the most important optimality for lobsters is "not to be broken". In the next section, an example of material design is given that using these efficient features of lobsters.

5. Material design

Utilizing the four extracted features, material design was performed 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, various material properties were assigned that assist stress dispersion. Finally the behaviors were compared with a standard model by FEM simulation.

5.1. Preparation of FE model

First, an FE shell model was prepared that consisting of seven parts (Figs. 6(a), (b)) made of material No. 002 (MAT_ORTHOTROPIC_ELASTIC), which is valid for modeling the elastic-orthotropic behavior of solids, shells, and thick shells. In the case of shells, the mass density, Young's modulus, Poisson's ratio, shear modulus and yield stress are required [5]. The input material data are shown in Tab. 2 and assume perfect isotropy. The open face, corresponding to the front face in Fig. 6(b), is restricted in all directions. Fig. 6(c) 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, three types of sections were defined associated with the lobster's features.

- High-stress sections: Parts 4, 6, and 7.
- Low-stress sections: Parts 2 and 3.
- Sections where strong impact occurs: Parts 1 and 5.

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, two types of modified material properties were defined for a materially optimized new model. Tab. 3 shows these properties in detail. The material MID2 is strongly anisotropic with the same Young's modulus as the original material in one direction but lower elasticity in the other two directions. It is also considerably lighter than the original material. These material properties were defined with reference to uni-directional carbon fiber reinforced polymer (CFRP) [4]. MID3 is

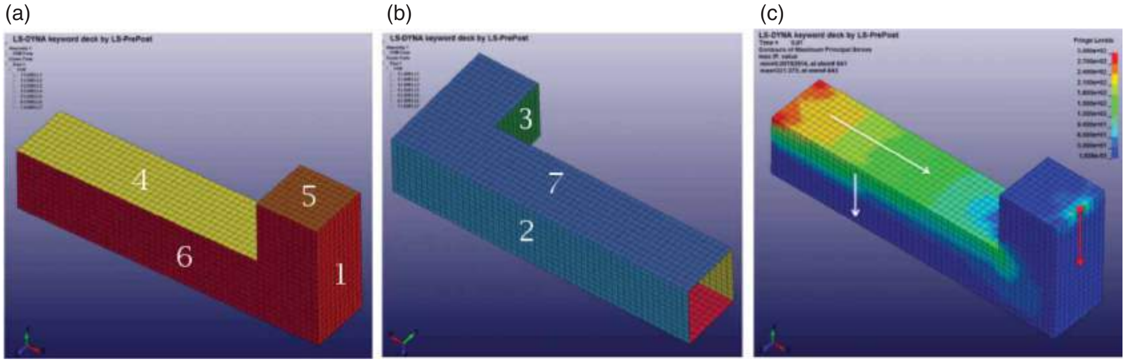

Figure 6. (a), (b) Geometry of the hook model with part numbers, and (c) contour map of first-principles stress.

Table 2. Material properties for original isotropic model. (RO: density, E: Young's modulus, PR: Poisson's ratio, G: shear modulus, SIGF: yield stress)

MID	RO	EA	EB	EC	PRBA	PRCA	PRCB	GAB	GBC	GCA	SIGF
1	4.00×10^{-9}	1.17×10^{5}	1.17×10^{5}	1.17×10^{5}	0.3	0.3	0.3	45000	45000	45000	600

Table 3. Material properties for optimized model. MID2: anisotropic material, MID3: weak and isotropic material.

MID	RO	EA	EB	EC	PRBA	PRCA	PRCB	GAB	GBC	GCA	SIGF
2	1.47×10^{-9}	$1.17e\times10^{5}$	$1.31e\times10^{4}$	1.31×10^{4}	0.17	0.02	0.4	4710	4690	4760	600
3	1.00×10^{-9}	3.00×10^{4}	3.00×10^{4}	3.00×10^{4}	0.3	0.3	0.3	11540	11540	11540	300

Table 4. Modified thicknesses and material properties for optimized model.

Part ID	1	2	3	4	5	6	7
thickness [mm]	0.3	0.8	0.2	0.8	0.3	0.8	0.8
MID	1	3	3	2	1	2	2

Table 5. Simulation results of original and optimized model.

	max first-principal stress [MPa]	max displacement [mm]	mass [g]
original model	321	0.40	3
optimized model	168	1.05	2.66

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, these materials were assigned and the thicknesses were modified for the new model as shown in Tab. 4. For sections in which high stress occurs, the anisotropic material was assigned considering the greater strength is given in transverse to the stress direction in each face (white arrows in Fig. 6(c)). A greater thickness was also assigned for this section. On the other hand, for sections in which low stress occurs, the weak and isotropic material was assigned to make the model as light as possible. Sections in which strong impact occurs should have strong material properties; thus, these sections were not modified from the original isotropic model.

5.2. *Simulation results and discussion*

Finally, a loading simulation was performed for the original model and the optimized model. A 200 N load was applied to the red point shown in Fig. 7(a), and the maximum stress at the blue points and the maximum displacement at the green point were recorded. Fig. 7 and Tab. 5 show the results of the simulation. As is clear from Fig. 7, the original model exhibits high stress in part 4 while the optimized model shows relatively low stress. Looking at the results in more detail, 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. An increase in displacement of this magnitude 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. Removing the fixed concept such as load bearing products should not deform and considering the most important and essential purpose we can obtain and utilize highly developed useful features from them.

6. Conclusion

In this paper it was reported that a method of extracting useful features from the lightweight structural design found in the American lobster. Tensile tests were performed on specimens cut from the crusher chela of lobsters using plastic clamps made by a 3D printer. Through

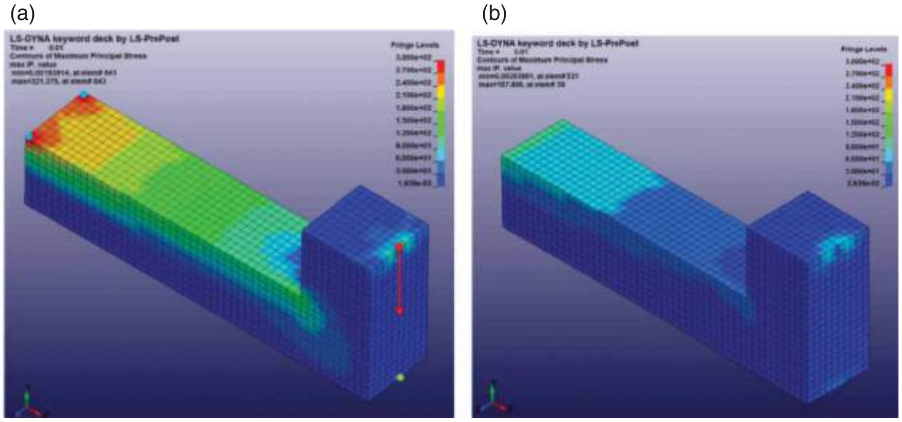

Figure 7. Contour map of first-principles stress. (a) Original model showing loading, stress, and displacement point. (b) Materially optimized model.

the tensile tests and analysis, it was found that the crusher has a material strategy of decreasing stress while permitting deformation. Applying this feature, a materially efficient and durable structure was formed 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. In addition, other type of material tests such as compression and bending are also our important future work since it would support to mimic the biological model more realistically with taking account of the original functions.

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