COMPUTER-AIDED DESIGN & APPLICATIONS
2018, VOL. 15, NO. 6, 841–851
https://doi.org/10.1080/16864360.2018.1462567

Material and structural design based on biological information using optimized stress distribution

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ABSTRACT
A design methodology based on biological information generally 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. This paper describes how to abstract a target creature and to construct computational model to simulate various cases for actual mechanical design.

KEYWORDS
Bio-inspired design; material design; optimization; inverse problem

1. 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 [5]. 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 [14]. However, there is little case that extracts and applies biological material features for designing industrial material or structure.

On the other hand, recent engineering materials or structures exploit heterogeneity, anisotropy and hierarchy that are features creatures originally possess. Analyzing these features in biological solids may give us some useful knowledge for engineering design. Therefore, in this study, a material design system based on mechanical characteristics in biological solids is constructed, and some designing demonstrations are conducted to validate usability of the system.

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. In addition, an optimization process is also integrated so that materials can be designed with the desired properties or functions. Such a general and flexible material design system is expected to be useful for utilizing the diverse characteristics of biological solids.

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 [9]. 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.

1.1. Outline of the proposed method

Here, the proposed method is briefly explained. Fig. 1 is a flowchart of the method. 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,

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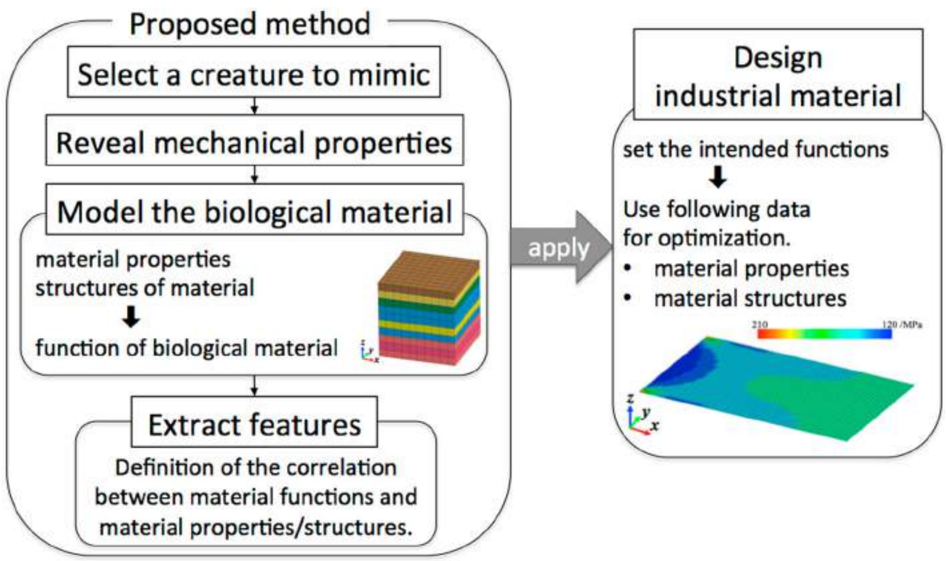

Figure 1. Flow of the proposed method.

and material models that exhibit the same deformation behavior as the actual biological material can be obtained. Through this 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 American lobster exoskeleton combines high mechanical strength with minimum material use and its features may inspire the design of lightweight materials.

1.2. American lobster exoskeleton

The features of the American lobster and its exoskeleton have been revealed from the standpoints of the material, morphology for consistency and functionality in previous studies. Here, we briefly describe its distinctive features and their applicability to a biomimetic approach.

1.2.1. Structure

Similar to other arthropods, American lobsters have hard exoskeletons that cover their body. The exoskeleton supports their body and also functions as armor. Lobsters use chitin and various proteins as the basic materials of their cuticle and form a hierarchical microstructure [1,4]. According to Fabritius et al. [3], 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. The 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. The outer layer, epicuticle is thin and waxy surface, which acts as diffusion barrier. On the other hand, exocuticle and endocuticle are designed to resist mechanical loads [11]. The exocuticle can be viewed as a harder and stiffer endocuticle with a higher mineral content and it has higher stacking density of the twisted plywood structure than the endocuticle [11]. The planar sheet making up the twisted plywood structure forms a honeycomb-like structure [13].

The lobster exoskeleton has a highly sophisticated hierarchical structure as mentioned above. In particular, it resembles fiber-reinforced materials in terms of (i) the fibers are embedded in a matrix, (ii) the anisotropic layers are stacked with their orientation gradually changing and (iii) layers that have different mechanical properties are combined.

1.2.2. Mechanical properties

To clarify the mechanical properties of the lobster exoskeleton, some material tests were conducted in previous studies. Sachs et al. focused on the honeycomb-like structure of the lobster exoskeleton and compared its deformation behavior with that of a general honeycomb structure through compression tests [12]. In their material tests, three types of specimen with different compression directions and observation directions were prepared to compare their multidirectional deformation behavior. In the tests, linear elastic deformation followed by plastic deformation was observed during compression in the out-of-plane direction. On the other hand, during in-plane directional compression, linear elastic deformation followed by a rapid increase in strain was observed, with the stress increasing extremely rapidly due to densification immediately before fracture. These deformation behaviors correspond to those of a general honeycomb structure, and it was revealed that the lobster exoskeleton material performs as an ideal honeycomb structure.

The above compression tests revealed macroscopic features that include the properties of the epicuticle, exocuticle and endocuticle. In contrast, Raabe et al. conducted microindentation tests on the cross sections of exoskeletons and clarified the different stiffnesses of the exocuticle and endocuticle [11]. Through the tests, it was revealed that the exocuticle possesses more than twice the stiffness of the endocuticle. It was concluded that this was caused by the difference between their stacking densities and the wall thickness of the honeycomb structure.

1.3. Fiber-reinforced plastics

Fiber-reinforced plastics (FRPs) are composite materials that consist of a plastic as the matrix and fibers as reinforcement. FRPs have outstanding mechanical properties compared with other composite materials because they can utilize the excellent mechanical properties of fibers. CFRPs have been widely utilized as high-strength lightweight material from the automotive industry to common electric appliances. Many CFRP products are produced using a prepreg, which is an intermediate base material that consists of carbon fibers and uncured resin. In particular, a prepreg that contains carbon fibers set in one direction is called a unidirectional prepreg and has been utilized to design layered materials. To design a layered material with the desired mechanical properties, it is necessary to set an appropriate direction for the carbon fibers when piling them up. For example, a material formed as a laminate of prepregs with the fibers oriented in one direction has anisotropy with high stiffness in a specific direction. On the other hand, a material formed while rotating the fiber direction has isotropic material properties. Such flexibility in material design is an advantage of CFRPs and other fiber-reinforced composites. However, to make best use of such flexibility, engineers should design optimum laminate configurations. Laminate configuration design is a combinatorial optimization problem that includes discretized fiber directions as variables and its calculation cost rapidly increases with the number of layers. The authors thought that some bio-inspired strategy can provide better solution instead of dealing with this issue as a complex optimization problem.

1.4. Analysis environment

In this study, we used two analysis tools to demonstrate the proposed method: One is LS-DYNA, which was used for inverse analysis and evaluation, and the other is LS-OPT, which was used for optimization. It should be noted that our method does not depend on specific software. One can reproduce the same results using arbitrary solver. LS-DYNA is a widely used commercial finite element (FE) solver that is able to carry out nonlinear analyses, for instance, crash analysis, drop analysis, forming analysis, and so on. LS-OPT is an optimization environment that works together with LS-DYNA.

2. Material design method

2.1. Material test

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 [15]. 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.

2.1.1. FE modeling

Half of a crusher without the dactyl (the part moved by a muscle) was modeled by CAD (Fig. 2), 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 [2], 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 chela and the loading force was set to 64 N. To form a compatible half

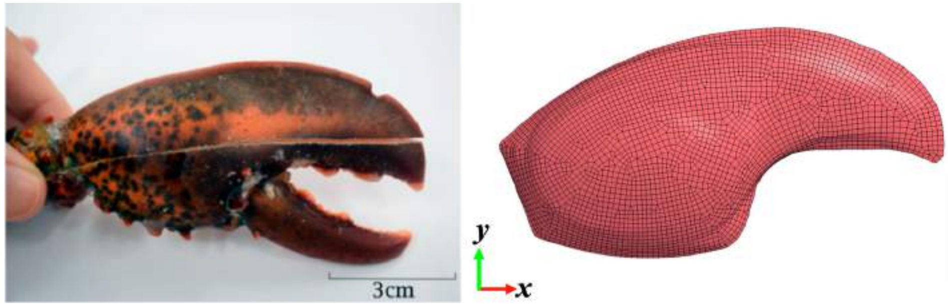

Figure 2. (left) Crusher chela of American lobster and (right) digital model of the crusher [15].

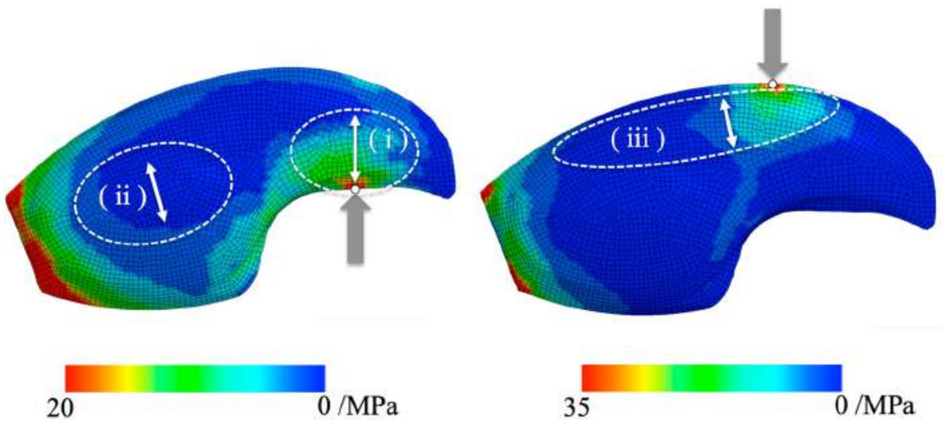

Figure 3. Contour maps of Mises stress in loading simulation. (left) Predation and (right) external impact.

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. 3 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.

2.1.2. Sample preparation and compression test

Considering the loads that occur when lobsters use their chelae, the compression load may be appropriate for assessing material properties. Thus, in this study, compression tests were conducted. The specimens used for the compression tests were taken from the crushers of American lobsters. The samples were cut into rectangular shapes of approximately 5 mm length and 2 mm width, and the unevenness of the circumference was removed by scraping as shown in Fig. 4(a). Then the specimens were fixed between two metal plates, of thickness 1 mm to prevent them from toppling during the compression tests. The experimental setup of the compression tests is shown in Fig. 4(b). The maximum capacity of the load cell was 620 N and the electric cylinder movesd downward at a speed of 0.5 mm/s. By measuring the load and stroke, it was possible to observe the stress-strain behavior of each specimen.

2.1.3. Results of material tests

Through the compression tests, the material properties of the specimens were obtained, specifically, the Young's modulus and fracture stress of the exoskeleton from the crusher chelae of the American lobsters. In these

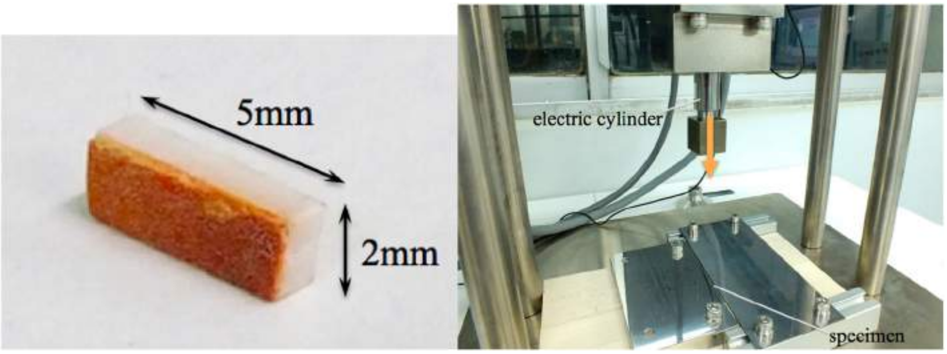

Figure 4. (left) Rectangular specimen and (right) experimental setup of compression tests.

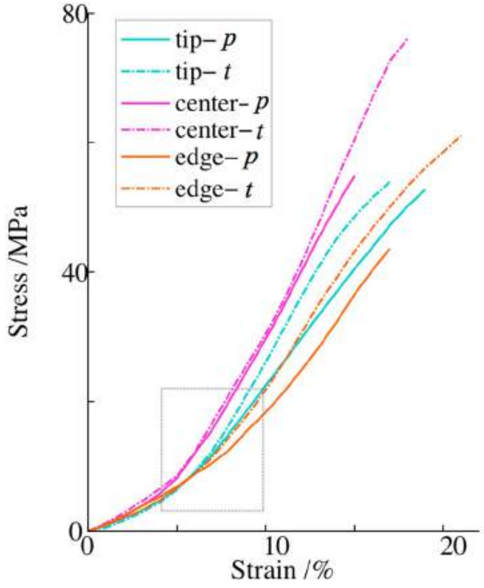

Figure 5. Nominal stress-strain curves. (*p*: parallel direction, *t*: transverse direction).

Table 1. Average Young's modulus and fracture stress.

	tip- *p*	tip- *t*	center- *p*	center- *t*	edge- *p*	edge- *t*
Initial Young's modulus /MPa	116	109	142	161	131	117
Medium Young's modulus /MPa	359	494	542	623	380	441
fracture stress /MPa	62.3	58.1	65.0	79.2	55.1	76.4

results, *p* and *t* indicate results obtained with the loading direction parallel and transverse to the stress flow direction, respectively. As shown by the nominal stress-strain curves (Fig. 5), all curves exhibited inclination with a strain of 5–8%. In other words, the Young's modulus increased at approximately this strain, which may have been due to the microstructure of the lobster exoskeleton having a honeycomb-like structure. This honeycomb-like microstructure may have undergone greatest deformation in the early stage of the test, after which the specimens exhibited the deformation behavior of a conventional material. From these results, the initial Young's modulus below 5% strain and the intermediate Young's modulus above 8% strain were calculated (Tab. 1).

Focusing on the results for the medium Young's modulus, it is clear that all parts exhibit higher stiffness and fracture stress transverse to the stress flow direction. This means that the lobster's exoskeleton is composed so that it deforms easily in the loading direction, which is required for the use of the crusher chela. By deforming rather than resisting when a load is applied, the lobster exoskeleton appears to avoid the worst-case scenario of being destroyed by a load.

The differences in the Young's modulus and fracture stress with the direction indicate the anisotropy of the material. Comparing the results for the three parts, there is a difference between the Young's moduli in the two directions, particularly in the tip. The tip of the chela has a characteristic function, which is to pinch preys; thus, the loading direction is restricted. Specialization for the expected load appears to produce this anisotropy, and a material structure optimized to maximize its effectiveness can be observed.

2.1.4. Structure observation

Structure observation by optical microscopy was also conducted to identify the thickness ratio of the three macroscopic layers, which are the epicuticle, exocuticle and endocuticle, as shown in Fig. 6. In this study, the exocuticle and endocuticle were particularly focused on because of their load-supporting function. Tab. 2 shows the results of the observation. According to the results, the total thickness of the tip is considerably larger than the other parts. Note that the thickness ratio of the exocuticle is approximately twice as large for the edge as for the other parts.

Through the compression tests and structure observation, some material properties were obtained for each part. In the following modeling phase, these material properties are utilized to generate a model for the material that exhibits the deformation behavior of each part.

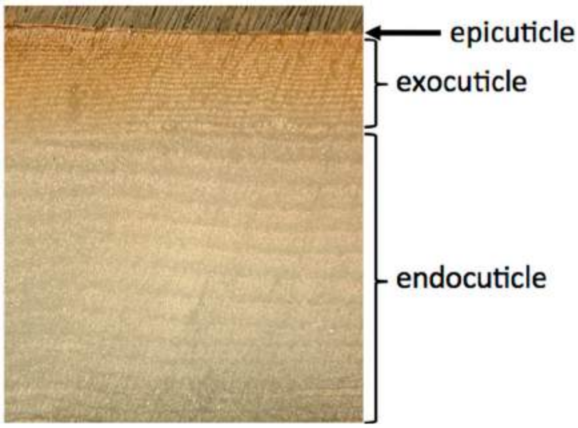

Figure 6. Cross sectional microphotograph of lobster's exoskeleton.

Table 2. Results of structure observation

	tip	center	edge
Thickness of exocuticle /μm	146	124	108
Thickness of endocuticle /μm	1334	835	424
Ratio of exocuticle among the whole /%	9.86	12.9	20.3

2.2. Modeling of biological material and feature extraction

On the basis of the results of the material tests, FE models of the biological material, the exoskeleton of a lobster in this case, were developed. In this section, a method for modeling a biological material that includes inverse analyses, which reveal material properties that cannot be obtained by material tests, is presented. First, a blank model was set as a base model and the material properties in each part (tip, center and edge) were input. After that, the model was compressed in FE simulations, similarly to in the material tests, and the indeterminate material parameters were identified. Through these processes, material models that exhibit similar behavior to the exoskeleton of a lobster were obtained. Using the results of the material tests and these biological models, the relationships between the mechanical properties and biological functions were considered. Finally, some mechanical features of the biological material were extracted from each part.

2.2.1. Layer model

Fig. 7(a) shows the blank model, which has 10 layers. One hundred solid elements constitute one model and the material properties obtained from compression tests were set for each layer. The material properties are explained in detail in the next section. In the compression simulations, the model was restricted and loaded in the x or y direction as shown in Fig. 7(b). Through these simulations, stress-strain behaviors were obtained as simulation results. To fit these simulation results with the experimental results, the indeterminate material parameters and layer patterns were optimized by inverse analysis, as described in the next section.

2.2.2. Inverse analysis

To model the deformation behavior of the lobster exoskeleton material more precisely, LS-DYNA material model No.26 (MAT26) was chosen because the exoskeleton has a honeycomb structure at the microscale [8]. Different approaches for modeling honeycomb structures by the FE method exist, which differ in terms of the modeling cost, computational cost and the accuracy of the results [6]. A detailed representation of hexagonal cells with shell elements can accurately predict the cell-wall deformation, but is unsuitable for large-scale models owing to the computational cost. A simpler method is to represent the cellular core as a homogeneous continuum using the effective orthotropic material parameters of the honeycomb structure. Although this method is not able to show detailed cell-wall deformation, it has

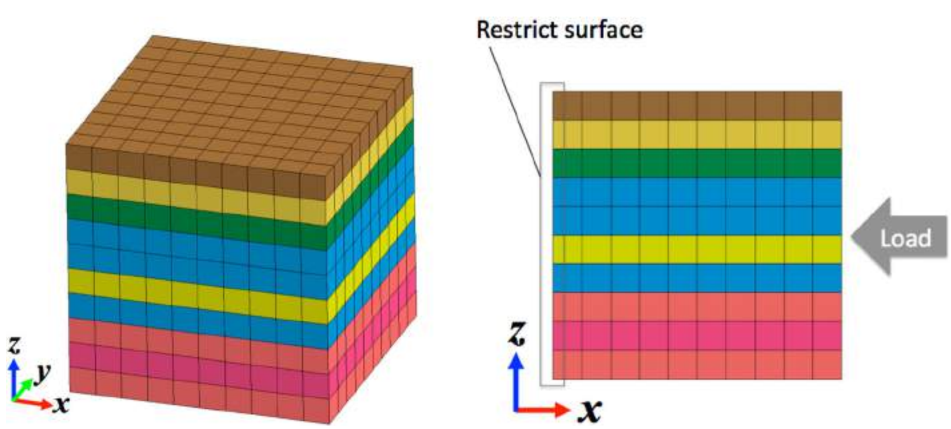

Figure 7. (left) Material blank model and (right) boundary conditions for compression in x direction.

Table 3. Main material parameters in MAT26.

E_x, E_y, E_z	Elastic modulus in *x*, *y*, *z* direction in uncompressed configuration
E_c	Young's modulus for compacted honeycomb material
ν	Poisson's ratio for compacted honeycomb material
V_f	Relative volume at which the honeycomb is fully compacted
σ_Y	Yield stress for fully compacted honeycomb

a much lower computational cost. The latter method, which assumes a honeycomb structure for the material, was chosen since details of the cell-wall deformation were not important in this study.

In MAT26, nonlinear elastoplastic constitutive behavior based on experimentally determined stress-strain curves can be defined separately for all normal and shear stresses. These stresses are considered to be fully uncoupled. Additionally, this material model included some parameters for a fully compacted phase. Because these material parameters could not be obtained in material tests, inverse analyses were conducted to identify them. Tab. 3 shows the main material parameters, where E_c, ν, V_f and σ_Y are parameters related to the fully compacted phase. To clarify the effect of these parameters on the analysis results, global sensitivity analyses were conducted. Consequently, E_c and V_f were selected as indeterminate material parameters.

Two values of Young's modulus were set for the fully compacted phase, one for the exocuticle and one for the endocuticle. Also some layer patterns consisting of materials oriented in two directions (0° and 90° material) were investigated to find the best solution. The stress flow of the 0° material was in the *x* direction and that of the 90° material was in the *y* direction.

2.2.3. Relation between mechanical properties and biological functions

The results of the inverse analyses are shown in Tab. 4. In accordance with our expectations, the magnitude of the correlation of E_c between each part is related to the Young's modulus obtained in the compression tests. Through these inverse analyses, material models that exhibit the same deformation behavior as an actual lobster exoskeleton were obtained.

To utilize these material models to design an industrial material, the functions and features of the material in each part were defined as follows:

Table 4. Optimized results of fully compacted material parameters.

	tip	center	edge
E_c in exocuticle /MPa	776	2302	625
E_c in endocuticle /MPa	776	999	539
V_f	0.669	0.631	0.684

Tip part: Avoid stress concentration by deforming while retaining the function of pinching prey.

Center part: Minimize deformation and protect internal structures from external loads.

Edge part: Avoid destruction of structures by permitting deformation caused by external loads.

On the basis of these features for the different parts, a material with a layer structure was designed, as discussed in the following section.

3. Implementation of material design

We set up a demonstrations with the aim of designing a more lightweight layer structure. 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: (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.

3.1. Design example 1

3.1.1. Setting of optimization problem

Fig. 8 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. 5. 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.

Fig. 9 shows the design target has been divided into three parts, which are explained previous. 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

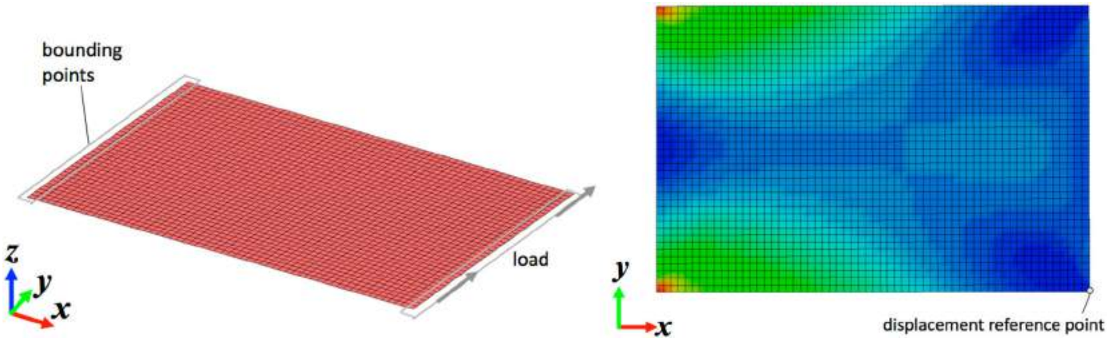

Figure 8. (left) Boundary conditions and (right) Mises stress counter map of initial model.

Table 5. Initial model data and analysis result.

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

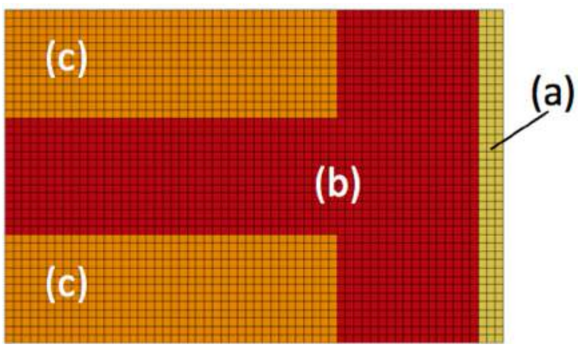

Figure 9. Divided model for the proposed method.

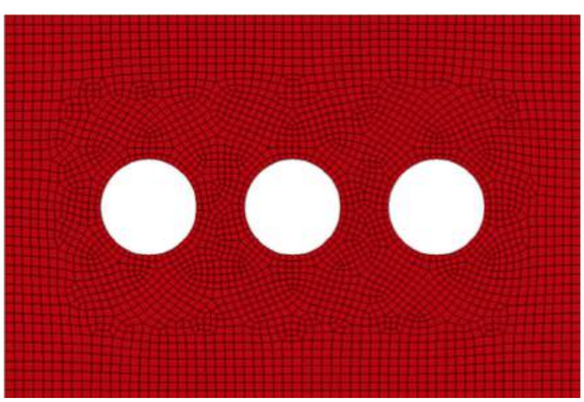

Figure 10. Perforated model for conventional method.

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. 10, 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.

Table 6. 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

3.1.2. Result and discussion

The analysis results obtained using the proposed method and conventional method are summarized in Tab. 6. Also the obtained Mises stress contour maps are shown in Fig. 11. The mass of the model optimized by the proposed method is lighter than that obtained by the conventional method, although there is a small increase in the displacement. In addition, the time required for optimization by the proposed method was considerably shorter than that for the conventional method. It took 235 sec. to obtain the solution in the proposed method and 588 sec. in the conventional method. This difference was due to the lower number variables in the proposed method.

These results mean that the proposed method can derive a solution that is comparable or superior to that obtained by the present method in a shorter time. Furthermore, in contrast to the conventional method, which optimizes the geometry and materials, the proposed method has the advantage of only optimizing the material layout, maximizing the efficiency of its use. This new approach provides new possibilities for the optimization of structures. By determining in detail the mechanical properties of creatures, appropriate design variables can be chosen and their numbers can be reduced to enable more efficient optimization.

3.2. Design example 2

3.2.1. Setting of optimization problem

As a second example, more complex boundary condition was attempted: a line load was applied in the normal direction of the center of the plate that was fixed at both ends, as shown in Fig. 12. In the same figure, the Mises stress distribution of the plate material before the design

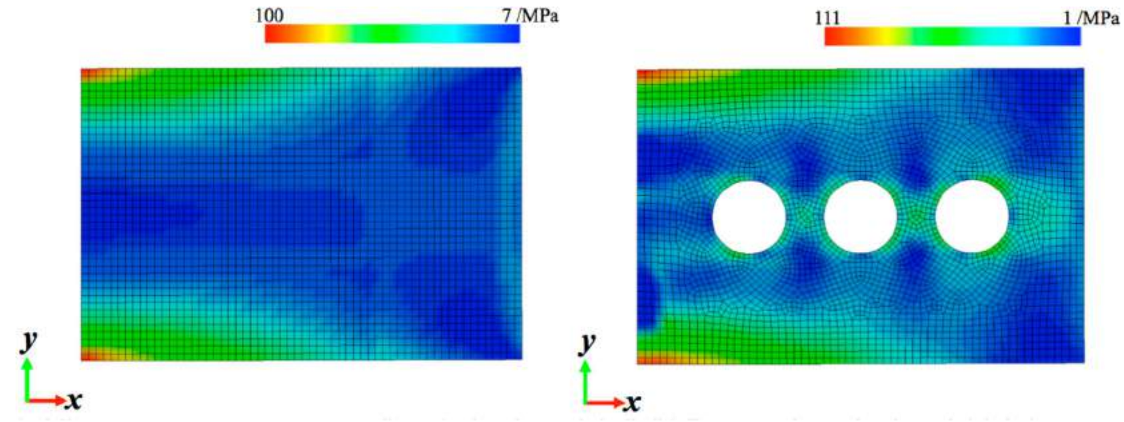

Figure 11. Mises stress contour map of optimized model. (left) Proposed method and (right) conventional method.

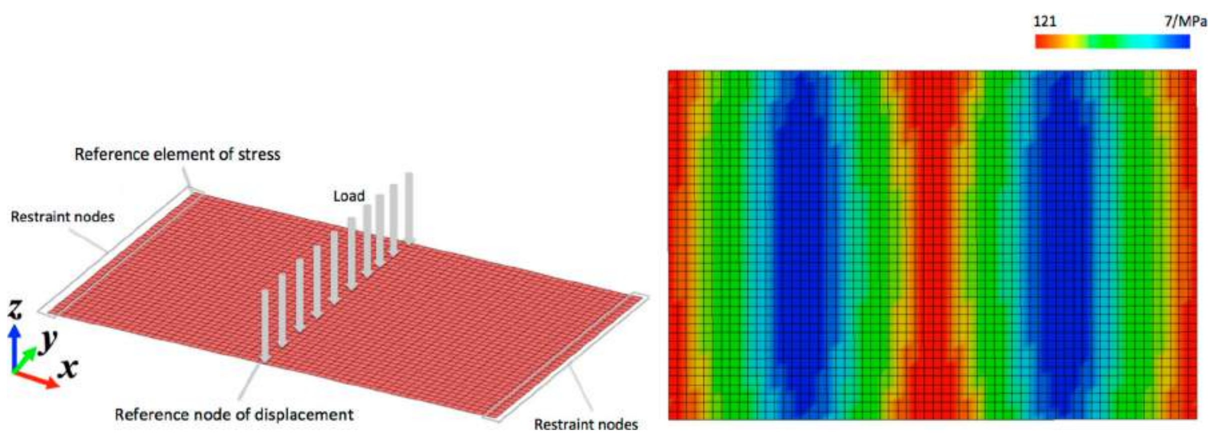

Figure 12. (left) Boundary conditions and (right) Mises stress counter map of initial model.

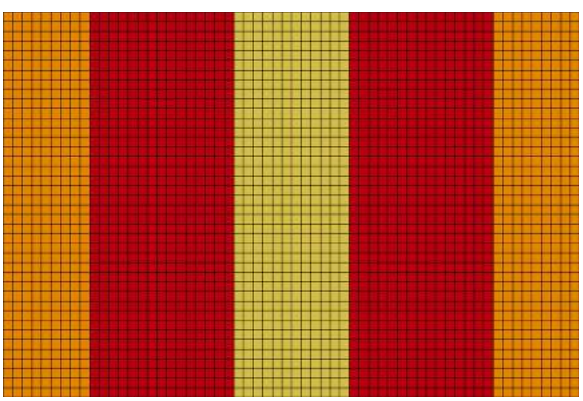

Figure 13. Material arrangement based on the stress distribution and bio-inspired strategy.

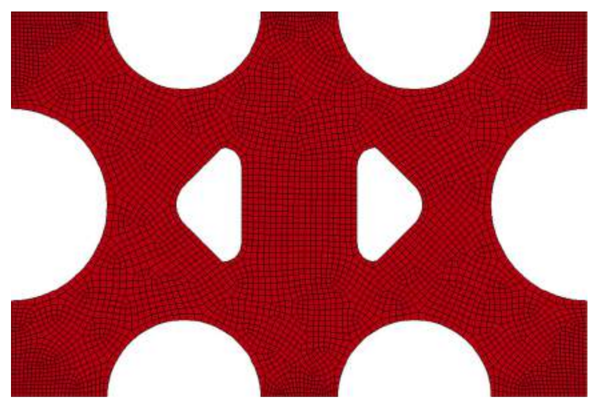

Figure 14. Perforated model for comparison.

is shown. Fig. 13 shows the design strategy of material arrangement according to the stress distribution.

Then, as a comparison, another plate model was created based on topology optimization [7], as shown in Fig. 14. In this model, to reduce the weight with maintaining sufficient strength, several holes were generated. Note that the used model is a two-dimensional version of

Table 7. Initial model data and analysis results of optimized model.

	Mass /kg	Stress/MPa	Displacement /mm
Initial model	2.57	121	2.51
Proposed method	0.854	97	4.58
Conventional method	0.962	129	2.98

that obtained in [7]. Next, as in Example 1, the proposed optimization scheme was performed with the thickness as a variable.

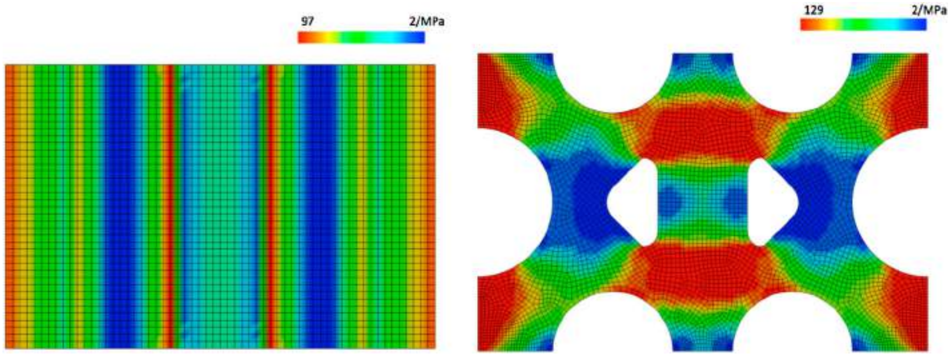

Figure 15. Mises stress contour map of optimized model. (left) Proposed method and (right) conventional method.

3.2.2. Result and discussion

The analysis results obtained using the proposed method and conventional method are summarized in Tab. 7. Also the obtained Mises stress contour maps are shown in Fig. 15. The proposed method that incorporates biological characteristics suggests an alternative solution that does not necessarily indicate total superiority to the conventional method. As seen from these values, the objective displacement increased compared to the conventional method, this is due to the strategy "reduce stress by permitting larger displacement"; therefore, the displacement reference point was replaced to the tip portion. Rather, it can be said that displacement can be controlled while maintaining rigidity by changing the arrangement of biological materials. From this point as well, the effectiveness of the proposed method was confirmed. However, the result of the proposed method exhibits a stress concentration at the boundary of different materials. Although apparently this is a problem in actual design, the use of hierarchical material design and gradually varying thickness may avoid this problem as in creatures in nature.

4. 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.

Using the proposed method and the features of the lobster exoskeleton, a layered structure was optimized to form a more lightweight model. Through comparison with the conventional method for lightweight design, it was shown that the proposed method can derive a solution that is comparable or superior to that obtained by the conventional method in a shorter time. Although the exoskeleton of the lobster was studied to design the CFRP layer structure in this study, the proposed method is not limited to this case and can also be used in other cases, focusing on arbitrary creatures and materials.

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