Modeling of the Bending Behavior to Study Nested-Cylinder Structure in Spicules

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Abstract The spicule structure of the *Euplectella aspergillum* sponge (EA) looks promising in the search for mechanical enhancements of brittle materials. Researchers have explored how the various structural levels of the EA affect the properties of the material. Specifically, the nested-cylinder structure of the EA's spicules increases the strength and toughness of the sponge. However, there is limited research on this structural level of the sea sponge. This research uses finite element analysis (FEA) to model the spicule structure in COMSOL, setting the stage for further research into this bio-inspired material. The results of the initial bending tests prove this procedure of analysis is useful in the study of the spicule structure.

Keywords Spicules · Mechanical properties · Modeling · Bending test · Finite element analysis

Introduction

Nature often provides novel inspiration for scientific inquiry. Structures like honeycomb and nacre have been mimicked to improve existing technologies [1, 2]. Each of these lightweight structures consists of a complex hierarchal architecture that enhances their mechanical properties [3]. Brittle, lightweight materials are organized in such a way that strength, toughness, and other features are increased.

The unique structure of glass sea sponges has exhibited these qualities under initial testing [4]. Significant progress has been made to understand the structure and properties of the *Monorhaphis chun*, a giant glass sponge with spicules up to

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three meters long [4]. Natalio et al. [5] showed how isolated spicules of a similar *Demospongiae* sponge were used to increase Young's modulus, stiffness, and fracture resistance of samples of pottery when oriented in specific directions. The study of each of these sponges has started a wave of progress to incorporating glass sea sponge structures into new architectures.

Each of the structural levels of the *Euplectella aspergillum (EA)* sponge (Fig. 1) has been shown to have similar elevated properties [6]. Woesz et al. [7] compared the *Monorhaphis chun* and the *Euplectella aspergillum*, investigating their individual structures and their mechanical behaviors; the study concluded that while both sponges have elevated mechanical properties, the structural distinctions of the two impact the properties in different ways. Rising off the surge of the investigation of biological composites, the EA sponge grasps the interest of materials science scholars.

Weaver et al. [8] investigate the largest organization of the EA, the siliceous skeletal lattice; they note that diagonal bracing, a ridge system, and a "holdfast apparatus" among other design elements account for increased mechanical performance. This provides a foundation for other researchers to dive into the implications of these complex design elements. Figure 2 shows the complex webbing of the spicule's lattice can be seen more clearly; its intricate design intrigues scholars, causing them to question how this structure can be applied to other materials. One study found that this lattice seems to provide exceptional support in comparison to the amount and type of material used [8].

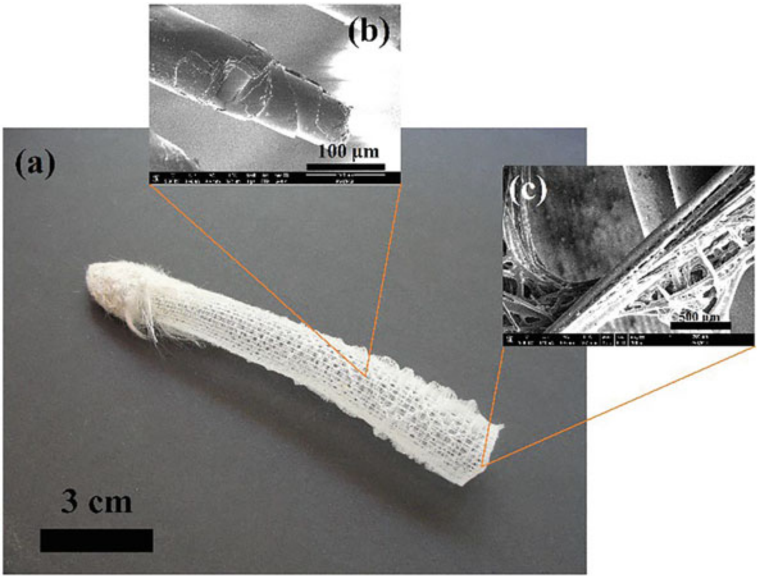

Fig. 1 Images of **a** the Euplectella aspergillum marine sponge; **b** concentric cylindrical structure of spicules; **c** macrostructure of the base of the sponge at higher magnification

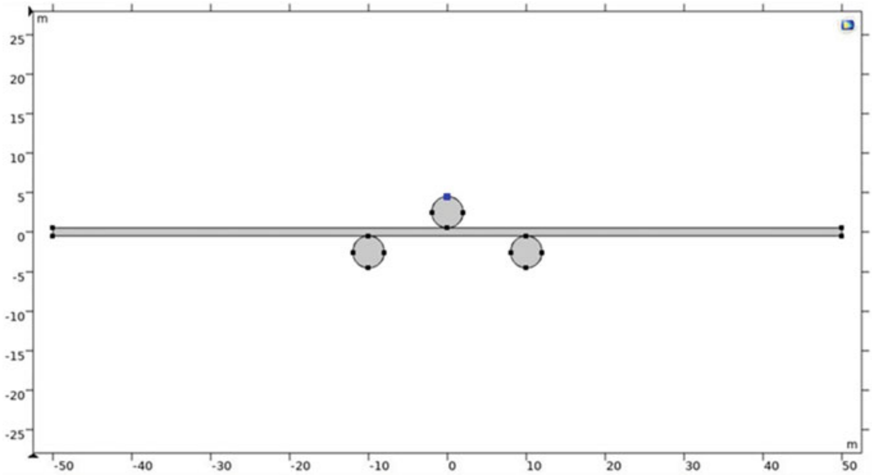

Fig. 2 2D rod geometry of a bending test in COMSOL

The individual strands of the crystal lattice of the EA are made of bundles of spicules [5]. Figure 1b shows the complex nestled-cylinder organization of a spicule. Scholars have investigated how the alternating layers of silica and organic material seen in the spicules' structure could increase mechanical properties compared to a solid rod. They have seen how this structure increases the strength of the brittle material [9].

The supposed correlation between the structural hierarchy of the EA and its enhanced mechanical properties excites scholars, but there are still doubts about the accuracy and significance of the previously obtained results and conclusions. Kochiyama et al. [10] questioned the fracture tests of the sponge's spicules, claiming that the "sawtooth patterns" are a result of the specimen slipping during testing and not an indication of multiple levels of fracture. Monn et al. [11] suggested that in the eagerness of finding enhanced biological composites, researchers exaggerate the significance of their findings; Monn et al. agreed that the structure increases toughness but wondered if the increase warrants further exploration. Amidst this controversy, researchers are exploring insightful methods to look at the various structural components of the EA from new perspectives. Brown et al. [3] recognize the shortcomings of current data; they use 3D scans of the EA specimen to create finite element analysis (FEA) models and 3D printing to mimic the spicule structure on a larger scale.

The microstructure of spicules is explored in this study through modeling. By first examining the scanning electron microscope photos of the specimen, detailed models are made with FEM to match the performance of the specimen in mechanical tests.

Methodology

In order to understand the mechanical properties of the EA spicule structure, the nested-cylinder analysis must be compared to that of a solid rod. COMSOL was accessed through the Penn State ROAR high-performance computer cluster. The solid mechanics physics module was used to simulate bending tests.

2D Rod

Using parameters for ease of modification, a 2D geometry of a simple rod was created. To simulate a bending test, three circles were oriented as shown in Fig. 2 in order to constrain the rod. The "form union" option was used to describe the relationship between the parts and appropriate materials were selected.

Using the linear elastic material module, the lower two circles were fixed, and a point load (F) was placed in the negative y direction on the top of the uppermost circle.

3D Rod

Using the principles from the 2D test, a 3D test was created in a similar fashion. A thin cylindrical rod was encased with three thick rods (Fig. 3). The "form union" selection was used for the entire geometry to allow for contact. In the solid mechanics module, a boundary load was applied in the negative y direction on the upper boundaries of the uppermost cylinder.

The lower boundaries of the lower cylinders were then fixed. In order to keep the upper cylinder from slipping, the displacement of the circular faces was prescribed as zero in the x and z directions.

Results and Discussion

2D Rod

Using a stationary study, the 2D rod setup was analyzed, obtaining the following results. Figure 4 displays the surface von Mises stresses and simulates the displacement of the rod under the load. The results are as expected with a stress concentration in the center of the three circles. The ends of the rod rise as a result of the load.

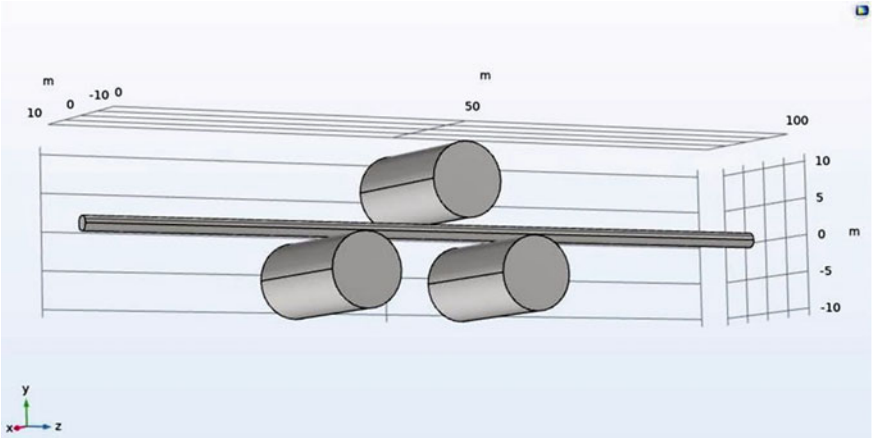

Fig. 3 3D rod geometry of a bending test in COMSOL

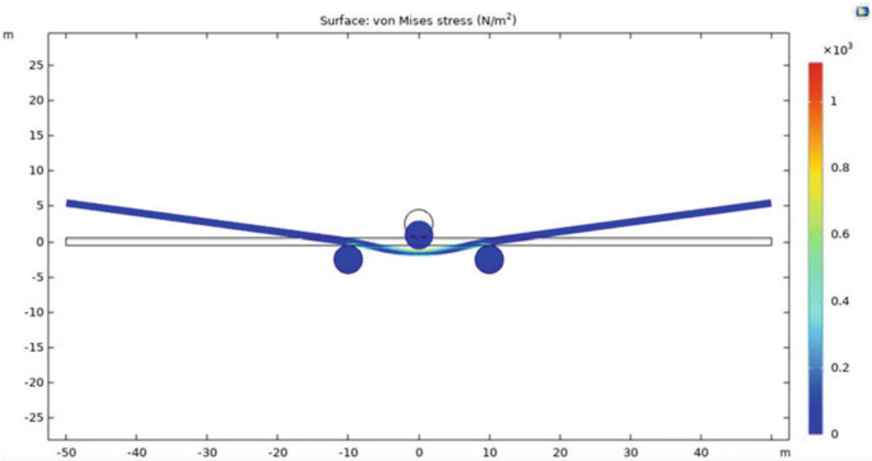

Fig. 4 Surface von Mises stress graph as a result of stationary study of 2D bending test in COMSOL

3D Rod

Figure 5 shows the results of the stationary study of the 3D rod. The bending of the rod under the applied force is seen as well as a graph of the surface von Mises stresses. Similar to the 2D rod, there is a stress concentration in between the three cylinders and the ends rise.

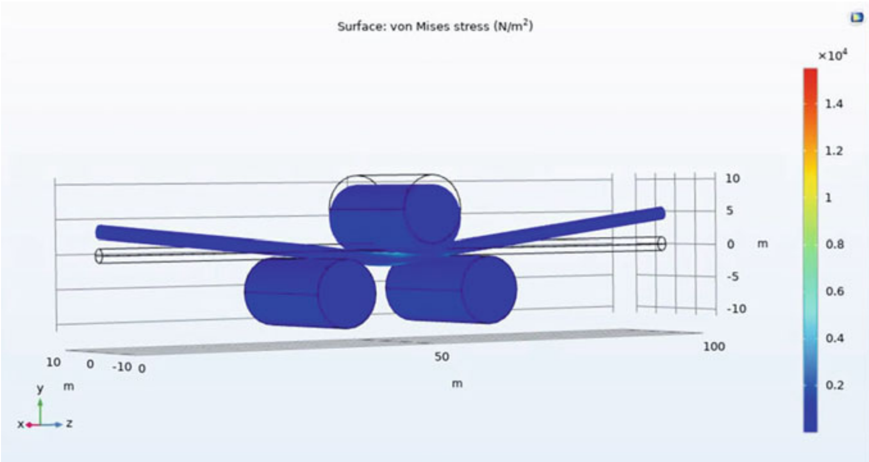

Fig. 5 Surface von Mises stress graph as a result of stationary study of 3D bending test in COMSOL

Future Analysis

While these results have some similarities to mechanical tests, additional physics must be added for an accurate comparison. The next step in the simulation is to add the damage module to mimic the fracture throughout the rod. Using the displacement and damage from the 3D rod simulation, one can obtain data with which to compare a nested-cylinder structure under a bend test. Following the methods outlined, further analysis is needed with layers of cylinders.

Conclusions

The goal of this study was to gain more understanding of the mechanical properties of the spicules of the *Euplectella aspergillum* sponge. By using a finite element analysis, outside factors can be removed to narrow down the cause of the enhanced properties of the spicule. This study provides a basic introduction to such a procedure. By starting with the solid rod as a control, there is an opportunity to simulate the nested-cylinder structure for comparison. That would allow one to compare mechanical properties purely from a change in geometry. As more is understood about the structure and properties of the spicules of the *Euplectella aspergillum*, the principles learned can be implemented in innovative designs. Among others, there are various potential biomedical applications for this structure including bone implants. Each study of the EA brings scientists closer to making these implementations a reality.

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