Morphogenesis and mechanostabilization of complex natural and 3D printed shapes

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The natural selection and the evolutionary optimization of complex shapes in nature are closely related to their functions. Mechanostabilization of shape of biological structure via morphogenesis has several beautiful examples. With the help of simple mechanics-based modeling and experiments, we show an important causality between natural shape selection as evolutionary outcome and the mechanostabilization of seashells. The effect of biological growth on the mechanostabilization process is identified with examples of two natural shapes of seashells, one having a diametrically converging localization of stresses and the other having a helicoidally concentric localization of stresses. We demonstrate how the evolved shape enables predictable protection of soft body parts of the species. The effect of bioavailability of natural material is found to be a secondary factor compared to shape selectivity, where material microstructure only acts as a constraint to evolutionary optimization. This is confirmed by comparing the mechanostabilization behavior of three-dimensionally printed synthetic polymer structural shapes with that of natural seashells consisting of ceramic and protein. This study also highlights interesting possibilities in achieving a new design of structures made of ordinary materials which have bio-inspired optimization objectives.

INTRODUCTION

Understanding biological structures toward nature-inspired design is an important field of research (1–5). Over the past several decades, numerous studies had been carried out to identify the scientific basis for the naturally adaptive growth of biological structures through environmental exposure of biomaterials and continuous optimization of the response of these biomaterials at various geometric length scales to satisfy specific environmental conditions (2, 6–11). A significant advancement has been made in recent years in this field of science, and it has led to important applications in defense and safety, automotive, and architecture (9–11). Several groups of researchers have reported detailed reviews summarizing these advancements (2, 6–12). Most biological materials consist of fascinating structure at micron and submicron scales (2, 6–17). Examples are the organization of nanoscale collagen fibrils in extracellular matrix structures, the two-level hierarchy of open cell structure in falcon feather, and many more (12–17). A series of interesting studies on the nacre shell has been reported. Nacre shells have a unique microstructure consisting of CaCO3 with organic molecules (13–21). Such kind of microstructure gives rise to enhanced mechanical properties including great strength with low mass density and great toughness (8, 21). This type of microstructure has been successfully incorporated in materials for defense and structural applications (2, 6–17). Biological structures naturally evolve into large macroscopic structures, and understanding of the underlying causality is challenging and of great importance. These natural macroscopic shapes are very different from the most common shapes (such as sphere, cylinder, and polyhedron) that we use in our engineering designs. The level of complexity in these biological structures clearly depends on the environmental conditions under which they evolve and adapt via continuous optimization. Clearly, there is hardly any direct sensory pathway in most of these biological structures to aid such adaptation; however, an evolutionary biological process follows. This paper is primarily concerned with the scheme of causality that drives natural biological evolution rather than the evolution process itself. To the best of our knowledge, the reason behind the macroscopic shape of the nacre shell remains unknown, and the complexity of such a shape is significant compared to the families of natural biological structures. How the environmental conditions alter and ultimately improve the mechanical response of the structure as the nacre shell grows is important, but yet to be analyzed. We assume that the metabolic process to accumulate biomass invariably favors the specific environmental conditions involving food and other essential supplies, besides favoring the primary factor, that is, the mechanical stimulation as in the case of nacre shell. Subsequent to this important aspect of the study, we further apply shape selection–related advantages in artificially engineered structural material and explore the possibility of creating stronger structures out of ordinary materials and comparing the behavior of these engineered structures with that of the natural biological structures. The engineered structures are manufactured by the three-dimensional (3D) printing of commonly used polymers. Future exploration to engineer these structures via a synthetic biology route may be of considerable interest to the scientific community.

Detailed studies involving experiments and simulations have explained the importance of the shapes of bones, bead shell, ladybug legs, kingfisher beak, boxfish, shark teeth, and many more (2, 6–17). The unique mechanical response of these relatively simple shapes has attracted major attention from the engineering community. These shapes and the associated mechanical concepts have been applied to protective shields, automotive parts, and building architectures (2, 6–17).

The evolutionary optimization of shape is one of the key approaches that natural species adopt for survival under varied environmental conditions such as changing mechanical load (8, 18–21). Morphogenesis via

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natural selection creates complex shapes that are important for various functions and adaptation. For example, shape engineering can provide novel architectures that help in damping high-impact collisions and protect objects or living species inside (1–11, 15–21). However, a clear understanding of the mechanical response of the naturally occurring complex shapes with respect to its evolutionary path is still lacking. Here, we have considered seashell, which is found abundantly near seashores, as an example of complex but fascinating shapes. There is a specific causality of such shapes in protecting the species inside the shell (22, 23), and this poses an interesting problem to be addressed. The shape of seashells has attracted attention among mathematicians, artists, and biologists (11, 24–27). Here, we have chosen two different shapes, namely, shell-1, which has a moon shape, also known as patelliform or bivalves, and shell-2, which has a screw shape that is famously known as Turritella or turbinate. Both these shells house a species of mollusks or snails. The samples are collected from the seashore of Pondicherry in the southern part of India. Various details of these seashells from the perspective of structural and materials engineering are given in figs. S1 to S5. The material composition and mechanical properties of various seashells have been characterized (8, 21). Depending on the growth and environmental conditions such as the levels of salt and other elements in seawater and age, the fractions of CaCO3 and organic compounds change, ultimately giving rise to various patterns of layers at nano- and microscales (8, 11, 18–26). The changes in the patterns and compositions give rise to different mechanical properties (8, 21). However, mechanical property variations due to these factors are probably not that significant among similar subspecies of seashells found in different parts of the world, and are hence a secondary effect as compared to shape selectivity, which is a primary factor in the shell structure’s response to mechanical load.

A detailed mechanical response of shell-1 subjected to underwater pressure is simulated and analyzed using the 3D finite element method (FEM). Subsequently, we grow synthetic polymer materials using the 3D printing method to realize an identical structural shape of shell-1. This is carried out to verify whether the material composition within the structural shape is the primary factor that controls the mechanical response or if the structural shape itself is the primary evolutionary outcome. Furthermore, 3D printing is adopted for creating this shape to explore new avenues in manufacturing bio-inspired structural shapes. Next, the analytical and synthesis approach explained above is applied to a more complexly shaped shell, shell-2. Shell-2 shows enhancement in its mechanical response that leads to better survivability under greater mechanical loads compared to that of shell-1. Such an evolutionary adaptation to enhance mechanical response by increasing the complexity of shape and the underlying causality is explained in this paper with the help of an analytical mechanics model.

The microstructural details of various regions of the seashells are analyzed using scanning electron microscopy (SEM), x-ray diffraction (XRD), and electron probe microanalysis (EPMA), and the results are shown in figs. S1 and S2. The microstructures of all these regions are found to be similar on the top surface, whereas the bottom surface is normally flat and does not reveal any pattern. Electron microscopy confirms the absence of microstructural inhomogeneity across the samples except for thickness gradation. Chemical composition analysis at various locations of the shell shows the presence of calcium (Ca), carbon (C), and oxygen (O) without appreciable variation in the composition. EPMA indicates the presence of Ca-based oxides (Ca, 54 ± 5 atomic %; C, 36±8 atomic %; O, 21±10 atomic %) (see the Supplementary Materials). XRD peaks measured at different regions indicate the presence of orthorhombic CaCO3 (Supplementary Materials). The conclusion based on these results is that material microstructure and inhomogeneity are less likely to contribute to the evolutionary mechanism toward the mechanical response of these seashells. These factors, however, can act as constraints on the evolutionary process. Hence, mechanical stress in the material microstructure must ultimately be the common link between structural shape and biological growth. We analyzed the mechanical deformation of these microstructures using microhardness tests with small loads (~50 g). The details of these tests are described in Methods. Hardness at various locations on the surface of shell-1 is in the range of 250 ± 20 HV (Vickers pyramid number) (fig. S4).

The organisms associated with the seashells grow in deep water and hence the shells are subjected to a much higher pressure compared to the atmospheric pressure. Protection of the organism’s soft body parts by its outer hard shell is a primary requirement (8, 11, 18–29). There are also other biological adaptation requirements to achieve locomotion: sensory functions, food intake, and survival (see fig. S5). Critical parts of the body, therefore, have to grow under such conflicting requirements. Shell-1 has a diametrically converging localization (defined in fig. S5), which is an optimal region for the growth of soft and locomotive parts of the body. To understand the reason behind such preferential localization, for protection of the soft body parts and the overall effect it imposes on the shape, we compare the deformation behavior of shell-1 and shell-2. 3D FEM is used to simulate the deformation behaviors. We first analyze the significance of the shape of shell-1. As shown in
Fig. 1A, there are two distinct features of shell-1 compared to a normal hemispherical shape. One of these corresponds to converging diametric localization toward the periphery, and the other is a system of periodic channels or grooves on the surface (see fig. S5). To clearly understand the importance of these two features in shell-1, we took a hemispherical shell, which is the simplest of all shapes, and compared it with a shell with converging diametric localization but without any groove on its surface, thus introducing a slightly higher complexity. Figure 2 (A to C), shows the finite element mesh (shown as inset) and the von Mises stress distribution on the surface of these structures with increased complexities. Figure 2A shows a symmetric stress distribution pattern for the hemispheric shape about its major and minor axes, whereas Fig. 2 (B and C), shows an azimuth symmetric but localized stress concentration pattern consistent with the diametric localization and center line between each pair of grooves of shell-1. Figure 2C shows higher stress and a nonuniform distribution (no directional preference) compared to that in Fig. 2B (stress is distributed or guided by the grooves). The minimum and maximum stresses observed are also greater for shell-1 (Fig. 2C) in comparison to the other two simpler shapes in Fig. 2 (A and B). That is, for a particular magnitude of pressure applied on these structures having increasing complexity (shell-1), certain regions remain under lower stress while a higher state of stress evolves in suitable and desirable locations. Ultimately, the microstructure must sustain such stress a concentration, and in the event of failure, it would still allow the soft body parts to survive in the least stressed region. One of the most widely used shapes in today’s structural engineering designs is the hemispherical one, which acts as a good load-transferring shape that easily transfers the applied load to its base structure on the edge. Although this is quite expected, what is not obvious is the reason behind the shell changing its shape from a hemispherical one to that with a diametrically localized or shrinking cross section. We hypothesize that the geometric localization evolves to distribute the external load suitably on the circumferential edge and more toward the diametrically localized region, thereby safeguarding the core cavity region and opening up the circumferential edge region for other biological needs. Details are marked in a vertical section of the shape shown in Fig. 2A. With further complexity introduced through the incorporation of the grooves, the stress gradient is further distributed or channelized in a directionally preferred manner in shell-1. The grooves help in the directional transfer of stress by distributing the stress over alternate concave and convex grooves (see fig. S5). The stress distribution across the grooves is shown in a vertical section of the shell (Fig. 2C).

Figure 2D indicates an increase in the maximum stress level as well as in the minimum stress level with increasing complexity of shape leading to shell-1 when its thickness is small (~0.5 mm as shown in Fig. 2E). The rise in maximum stress level due to increasing complexity confirms the evolutionary outcome that the stress-induced fracture of the shell-1 is localized at regions away from where the soft part of the body survives. Figure 2E shows the adaptation of shell-1 to stress levels as it grows and as the thickness of the shell increases. With an optimal thickness of ~1 mm, shell-1 reduces the magnitude of stress levels at the circumferential edge to enable easy locomotion that governs the evolutionary optimization needs. A more detailed mechanistic explanation of this phenomenon will be given later.

As described in previous studies (30–35), the thickness of the shell varies, depending on the age of mollusks (species that grows with shell-1 as its outer body). The thickness of the shell is a result of the internal growth of biominerals and proteins, controlled by the tissues underneath the hard shell and by external pressure, temperature, pH, etc. To better understand growth in terms of thickness to improve the stress distribution, we have simulated the stress distribution of shell-1 with increasing thickness and under a pressure of 0.1 bar, as shown in Fig. 2E. The stress level quickly saturates as the shell thickness increases beyond ~1 mm in the present samples of shell-1. For ~1-mm thickness of shell-1, the difference between the maximum and the minimum stresses is also greater compared to that for the other greater thicknesses. Figure 2C also shows the maximum stress being distributed along the convex ridges confined by two successive channels. Compared to the stress distribution shown in Fig. 2 (A and B), this type of directional stress transfer via alternate distribution of maximum and minimum stresses ultimately provides a greater stress-carrying capacity with localized failure rather than a complete collapse of the shape. This regimen of stress (~15 to 120 m of sea depth) and thickness (~1 mm) resembles that of the morphology of most natural seashells. The species living inside the shell biologically regulates the shell thickness, a process encoded in the cellular pathway of that species to achieve optimum protection. The protection requirement reduces as the species grows further, and hence the shell thickness saturates, explaining why the larger thicknesses are not typically found among these seashells.

As explained earlier, the diametrically converging or shrinking region holds the two halves of the shell together under the externally applied pressure under water, whereas the rest of the circumferential edge dividing the two halves can easily open and close (see fig. S5). The core cavity hosting the living species is not supposed to be subjected to enormous pressure. To demonstrate this on a scientific basis, we show a simple simulation in Fig. 2 (F and H). The simulation idealizes the load transfer from one-half of the shell to its circumferential edge held rigidly. This condition is simulated by considering a flat aluminum block as the rigid base. We plot the stress pattern induced on an aluminum block placed at the bottom of the shell. The three shells with a geometry of increasing complexity transfer the stress from their top plateau region to the circumferential edge region. The stress pattern on the hemispherical shape is symmetrical, and greater stress accumulates circumferentially, covering most of the bottom contact surface of the plate. This leads to a greater chance of damaging a weaker material base if attached to the bottom. The shell with only the diametrically converging shape but without the grooves actually concentrates greater stress at three distinct regions circumferentially at the base, thus leaving a greater area with lower stress in the base material. Finally, the natural shape of shell-1 enables even a small region to have high stress, which occurs precisely at the diametric localization region on the circumference. As a result, a much less stress is experienced in the central cavity region, and hence the living species at this location is safer compared to those in other shapes.

For the second type of shell with helical morphology (shell-2), the helicoidally concentric end is supposed to provide protection to the soft body parts of the species. We have compared the stress distribution with its counterpart geometries which have simple shapes, that is, a solid cone, and then an intermediate complex shape with a hollow cone structure with similar variation of diameter as shown in Fig. 3. The solid cone in Fig. 3A shows less variation in stress pattern relative to that of a hollow cone (Fig. 3B). The stress distribution in shell-2 shows a totally different behavior compared to that in the solid and hollow cones, as shown in Fig. 3C. It clearly localizes the stress predominantly on the first ring, and the rest of the rings remain more or less unstressed. A cut section of shell-2 is shown in Fig. 5H that reveals greater stress is taken by the inner helicoidal surface. Hence, this...
becomes more efficient in protecting the outer surface against high stress as compared to the simpler shapes shown in Fig. 3 (A and B). The maximum and minimum stresses are plotted in Fig. 3D. The results suggest that the natural shape of shell-2 distributes greater stress from the outer wall to the inner core wall, which is not possible in the other two simpler shapes. This is because of the continuously changing diametrical turns and the helicoidal surfaces of shell-2.

To understand the role of shell thickness in stress distribution in the case of shell-2 similar to what we have analyzed for shell-1, we have performed simulation with varying thickness. Figure 3E shows the optimal growth of thickness that is required to reduce the difference in maximum and minimum stress levels. In Fig. 3E, we observe that for thicknesses greater than ~1.5 mm, the stress levels tend to saturate, and so is the extent of stress transfer from the outer surface to the inner core of the helicoidal turns. Hence, natural shape selection goes hand in hand with thickness selectivity as the shell grows thicker.

A mechanics-based predictive model is used to explain the relationship between stress transfer path and shape and thickness selectivity, and to provide further scientific insight on natural shape selection as an evolutionary tool of enhanced survival. First, a simplified elemental segment of shell-1 is considered in comparison with a simple hemispherical shell as shown in Fig. 4 (A and B). The flexural stress in the simple shell segment is denoted as $\sigma_{xx}^{(1)}$ and that in shell-1 with grooves is denoted as $\sigma_{xx}^{(2)}$,

$$\sigma_{xx}^{(1)} = \frac{h_1 M}{2 I_1}$$

$$\sigma_{xx}^{(2)} = \frac{h_2 M}{2 I_2}$$

where $M$ is the applied bending moment as a function of pressure, $h_1$ and $h_2$ are the thickness of the simple shell and shell-1, respectively, and $I_1$ and $I_2$ are the second area moments expressed as:

$$I_1 = \frac{1}{12} \lambda h_1^3$$

$$I_2 = \int_{z=0}^{z=h_2} z^2 dA$$

Here, $\lambda$ is the segment length, and $z$ is the thickness coordinates measured normal to a reference
Using the above relation, the ratio of the flexural stresses can be expressed as:

\[ \frac{\sigma_{xx}^2}{\sigma_{xx}^1} = \frac{h_2 I_1}{h_1 I_2}. \]  (5)

Figure 4C shows the variation of stress in both shapes as a function of change in volume by keeping \( \lambda_1 = \lambda_2 = \text{constant}, Z_2 = Z_1 \) constant, and by varying the groove height \( Z_2 \). The grooves are idealized as a segment of half sinusoid and flat bottom channel as shown in Fig. 4B. This graph clearly shows exponentially higher stress accommodation per unit increase in volume of material used due to deeper grooves.

To explain the evolutionary mechanics in shell-2, which consists of two important shape combinations, first we consider the spherical segment followed by the conically spread segment as shown in Fig. 4D. Under an applied load \( P \), the two tangential reaction forces, \( F_1 \) and \( F_2 \) (as shown in figure), at the base can be determined as:

\[ \frac{P}{\sin(\theta + \phi)} = \frac{F_1}{\sin(180 - \phi)} = \frac{F_2}{\sin(180 - \theta)}. \]  (6)

The reactions are resolved into two components as shown in the figure. The normal stress is determined as:

\[ \sigma_{(1)} = \frac{P \cos(\theta - \Delta \theta)}{h \sin(2 \theta - \Delta \theta)} \sin^2 \theta \]  (7)

\[ \sigma_{(2)} = \frac{P \cos \theta}{h \sin(2 \theta - \Delta \theta)} \sin^2 (\theta - \Delta \theta) \]  (8)

where \( \Delta \theta \) is the difference in the angle posed at the center of the curvature caused by the progressive changing of that curvature from left to right in the helicoidal shell segment. Figure 4F shows the variation in the stress due to variation of \( \Delta \theta / \theta \). This graph clearly shows that greater asymmetry gives rise to a greater difference in stress distribution. As a result, the stress is greater for a shape with a larger radius. The stress gets further locked or localized in the current radial segment when the next radial segment along the cone has a significantly smaller radius. Therefore, the second type of geometric complexity of shape allows the structure to protect the smaller-radius part of the shell. Finally, in Fig. 4 (G and H), we show how a larger-radius shell takes a greater magnitude of stress on its circumferential edges.

The above theoretical details explain the reason behind the evolutionary optimization of shapes, such that the high magnitude of stress is directed and localized at certain regions of the structure. It allows fracture to only occur at a particular portion or at one geometric location, and therefore protects the species inside the shell. At the same time, it achieves a significant improvement in load-bearing capacity as compared to the simple shapes.

To support the above hypothesis regarding natural shape selection, we performed mechanical compression tests on the shell structures and compared the results with the load-bearing capability of basic materials (that is, CaCO3). At the same time, the evaluation is also extended to a completely different class of materials assembled synthetically using a 3D printed polymer structure of the same shape and dimensions. For the 3D printing, we have used a biodegradable polymer known as poly-lactide (PLA) (35–38), which is one of the highest consumed e-bioplastics in the world. It has a crystallinity of 37% with a melting point between 173° and 178°C and an elastic modulus of 2.7 GPa. Using PLA, the natural shape is printed using a 3D printer that is controlled with a computer. The in-house assembly of the 3D printing (39–46) machine...
uses a heater to melt the PLA, and prints are shown in video S1. Further details about the process are described in Methods.

Figure 5 shows the compression test results comparing the stress-carrying capacity of the natural shapes as compared to that of simple shapes for both natural structures and the artificially created structural shapes by 3D printing. Figure 5 (A and B), shows the compressive load versus elongation plots for the natural and the 3D printed shell-1. First of all, the natural shell-1 and shell-2 in Fig. 5 (A and C), have sustained a load of 250 and 130 N, respectively (for the given area under compression test). For the similar contact area as compared to shell-1 and shell-2, CaCO3 ceramic can take a maximum of 130- and 70-N loads, respectively. The loads are calculated using the yield strength of standard CaCO3 in standard cylindrical shape multiplied by the respective contact areas for shell-1 and shell-2. These results show that the complex shapes can sustain loads that are nearly twice as high as their basic material constituent and their respective counterpart simple shapes. The load versus elongation curve for the 3D printed PLA shell-1a and shell-2 shows a maximum load of 360 and 550 N, which are nearly three and five times higher, respectively, than that of a 6-mm-diameter wire made of PLA. This effect is due to compression of the vertical region (short column) of the curved segments in shell-1 and shell-2, wherein PLA first undergoes hardening (increasing slope of load-deformation curve), followed by transverse shear failure at the contact region, which is unlike brittle fracture without any hardening in natural ceramic. The above observation further confirms our hypothesis of the high stress-carrying capacity of these complex shapes, whereas the availability of natural materials acts as an evolutionary constraint in the natural shells. This can be an interesting tool for bio-inspired design via a synthetic biology route. Compared to the natural shell, the 3D printed polymer shows even better enhancement of overall load-carrying capacity due to geometrically induced material hardening as compared to ceramic. The effect of layer-by-layer deposition of polymer as compared to that of ceramic may have a role in microstructure, deformation, and failure behavior. To understand the protection mechanism offered by the complex shapes, the fracture behaviors of the natural and 3D printed shells are compared with our simulated results. Figure 5E shows the stress concentration at the left edge of simulated shell-1, which is similar to the results obtained in the compression tests of the natural shell-1 as well as the 3D printed shell-1. Figure 5H shows the simulated stress bands oriented at an angle of about 45°. The compression test results also show a similar 45° angle crack in the natural shell-2 as well as in the 3D printed shell-2.

In conclusion, we have explored the mechanical reasons behind the natural choice of particular size and shape in natural seashells. The 3D FEM analysis followed by a simplified analytical solution reveals the effect of such morphogenesis in terms of stress distribution. Our analyses show how the complex shape selection prefers spatial arrangement of soft body parts for protection under increasingly intense underwater pressure while at the same time enabling efficient locomotion and other biological interaction with the external ecosystem.
Mechanical testing using natural as well as 3D printed shapes further confirms this. We used PLA-based 3D printed polymer biomimetic structures that have shown even further improvements in the mechanical load–carrying capacity as compared to the natural composite made of biomaterials and protein. The study could provide new approaches to developing structural components with complex shapes by mimicking natural shapes that have evolved to provide mechanostabilization in living species.

Finally, we present a mechanics-based model to explain the evolution of two complex shapes in shells as they grow in nature. Such complex shapes play a crucial role in stress transfer and in enhancing the safety of the living species residing inside from extreme conditions. Using this understanding, we have fabricated similar shapes, using synthetic materials with the help of 3D printing, that yield superior properties as compared to the conventional shapes. The present study opens up pathways for designing new architecture for structural applications.

**METHODS**

**Simulation details**

Precise dimensional measurements of shape were performed using a Vernier caliper, whereas that of surface patterns were done using SEM. Using these measured values, the two shells were drawn in Catia V5 (the generative shape design module).

**Modeling of shell-1.** A number of planes were drawn with respect to a reference plane at different angles. In each of these, curved lines were drawn, all originating from a single point. The radius of the curvature varied in each plane so as to get an approximate model of the naturally occurring shell. After all the lines were generated, a surface was generated over all the lines, so that they appear similar to the natural shell.

**Modeling of shell-2.** A cone was generated, and on the surface of the cone, a helix of variable pitch and number of revolutions was generated. The cone was then suppressed, and only the conical helix was made to be visible. After this, a circle sketch was generated at the beginning of the conical helix. An adaptive sweep tool was used to sweep the circle at various diameters and the conical helix as the guide curve, thereby generating the approximate model of natural shell.

The modeled shell was then analyzed in Ansys 14 workbench. The module used was static structural for all the simulations. In all the simulations, a pressure of 10,000 Pa was applied on the surface of the shell. The von Mises yield criterion was used to analyze all the simulations. Simulations

![Fig. 5. Experiment and simulation.](image-url)
were also done by varying the thickness of the shell. The material properties for the shell were user-defined with an elastic modulus of 70 GPa and a Poisson’s ratio of 0.33. For the experiments involving the plate, from the general material library in Ansys 14. The edges were fixed, and the pressure was applied perpendicular to all points on the curved part of the shell. A compression test was performed to verify the FEM results. The conditions of the compression setup must be similar to the simulation setup. Therefore, boundary conditions were chosen such that they are the closest approximation to the compression setup.

**Experimental details**

The natural shells were washed with water and cleansed before analysis. An environmental SEM (FEI) with a lower voltage of 5 to 15 kV was used for microstructural analyses. The composition was measured using a field emission gun–electron probe microanalyzer (JEOL). The XRD was performed on a Cu Kα target using X-Pert Pro. The hardness measurement of shell-1 and shell-2 was performed using a CSM indenter under a load of 50 g. The hardness machine was calibrated using standard samples.

The modeled shell was then subjected to 3D printing, which uses a 3-mm-diameter rope PLA polymer as the stock. The heater was attached to a nozzle of 300-μm diameter. The nozzle was heated at 200°C for printing. The 3D axis of the nozzle is controlled using computer-controlled step motors. The computed design was printed layer by layer as shown in video S1. The natural as well as 3D printed shells were subjected to compression tests at a strain rate of 10^{-3}/s using a Dartec servo-hydraulic machine. A layer of cello tape was wrapped around the sample to prevent spreading of the broken pieces and also to view the cracks easily. The broken pieces of the natural shell were examined by SEM to evaluate the structure and the cracks that are present in it. Finally, XRD and hardness tests were performed on the natural shells.

**SUPPLEMENTARY MATERIALS**

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/1/e1400052/DC1

Fig. S1. (A) SEM images of shell-1 at different magnifications and of different regions. The selected areas are shown in the micrograph. (B) Images of subsurface at different locations after breaking it. (C) Back surface of shell-1.

Fig. S2. Micrograph of shell-2 at different magnifications and of different regions. The selected areas are shown in the micrograph. A representative composition spectra showing Ca, C, and O in the sample.

Fig. S3. A representative XRD plot of the natural shell. The samples are collected from different locations.

Fig. S4. Vickers hardness map of shell-1 and shell-2 showing hardness variation at different locations.

Fig. S5. The naturally occurring condition of shell-1 and its nomenclature used in the current work. Video S1. Stress distribution of the shapes under pressure.

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