Bioinspired design of shell structures: a lesson from echinoids

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Abstract

The main goal of form-finding shell structures is to determine the geometry of the shell mid-surface so that applied loads can be equilibrated mainly by membrane actions. An optimal configuration of the structure can be found for a specific load case and it is unlikely adaptable to all load conditions which a real structure is expected to undergo.

However, a limitless diversity of optimized shell structures, designed to effectively bear a vast variety of loading conditions, can be found in nature. Many living organisms employ protective shells against predators, and some of them, *e.g.* Acanthocardia, Pecten or Tridacna sea shells, use corrugation as a strategy to optimize structural performance of their shells. The efficiency of shell corrugation has been well employed in [1] to ensure existence of a load path that carries any variation of loading conditions by membrane actions only.

A very complex shell structure characterizes the calcitic test of echinoids, a class of marine organisms known as sea urchins and sand dollars. They underwent an incredible adaptive radiation, and specialized in variable forms and life styles to live in different marine environments. Geometries and structures evolved to efficiently withstand biotic and abiotic actions that load on these organisms.

We employed high-resolution X-ray micro-computed tomography, scanning electron microscopy, digital modeling, finite element simulations, and parametric design in order to understand and reproduce the structural behavior of regular echinoid's shell test. The optimization process conducted by natural selection and evolution on these marine organisms serves as an inspiration for designing light and efficient shell structures capable to bear a large variety of loading conditions mainly by membrane actions and limited bending stresses.

The proposed design approach combines classical form-finding algorithms, based on the Thrust Network Analysis [2], with the introduction of hinged connections inspired by those developed by sea urchins and sand dollars to reduce bending actions within their endoskeletons. The next step is to reproduce and repeat specific geometric elements by means of parametric design algorithms. Such a bioinspired design methodology is verified for a series of practical examples where the generalized eccentricity approach proposed in [3] is employed to estimate the magnitude of bending stresses.

References

[1] T. Michiels, S. Adriaenssens, M. Dejong, "Form finding of corrugated shell structures for seismic design and validation using non-linear pushover analysis", Engineering Structures, vol. 181, pp. 362-373.

[2] F. Marmo and L. Rosati, "Reformulation and extension of the thrust network analysis", *Computers and Structures,* vol. 182, pp. 104-118, 2017.

[3] S. Gabriele, V. Varano, G. Tommasiello and D. Alfonsi, "R-Funicolarity of form found shell structures", *Engineering Structures*, vol 157, pp. 157-169, 2018.