Re-Design Natural Structures: Structural Morphology using Methods of Structural Optimization

Advances in Architectural Geometry
Paris, France
September 27-30,2012

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Motivation / Introduction

Nature has developed a great variety of very lightweight structures, resulting from optimization procedures running over years and decades. Methods of structural optimization provide ways to simulate these procedures and thereby to grasp their basic structural behaviour. The merging of studies of natural structures with the methods of structural optimization can produce a new morphology of natural lightweight structures. Lightweight structures must and will play an important role in architecture and engineering due to the increasingly limited availability of building resources.

Numerous designers and researches refer to nature as an antetype for optimized lightweight structures. Richard Buckminster Fuller, Max Mengeringhausen, Frei Otto and Robert Le Ricolais have contributed important views of artifacts emulating principles of nature. Frei Otto and his team carried out systematic studies using physical models, which are very descriptive and aesthetic at the same time. Graphical and physical methods were an ostentative tool for the basic understanding of natural lightweight structures.

A comparable systematic study can nowadays be carried out using Finite Element models in combination with methods of structural optimization. The studies with varying loading or support conditions, comparable to the physical models, produce three-dimensional structures of high quality both in aesthetics as well in structural performance.

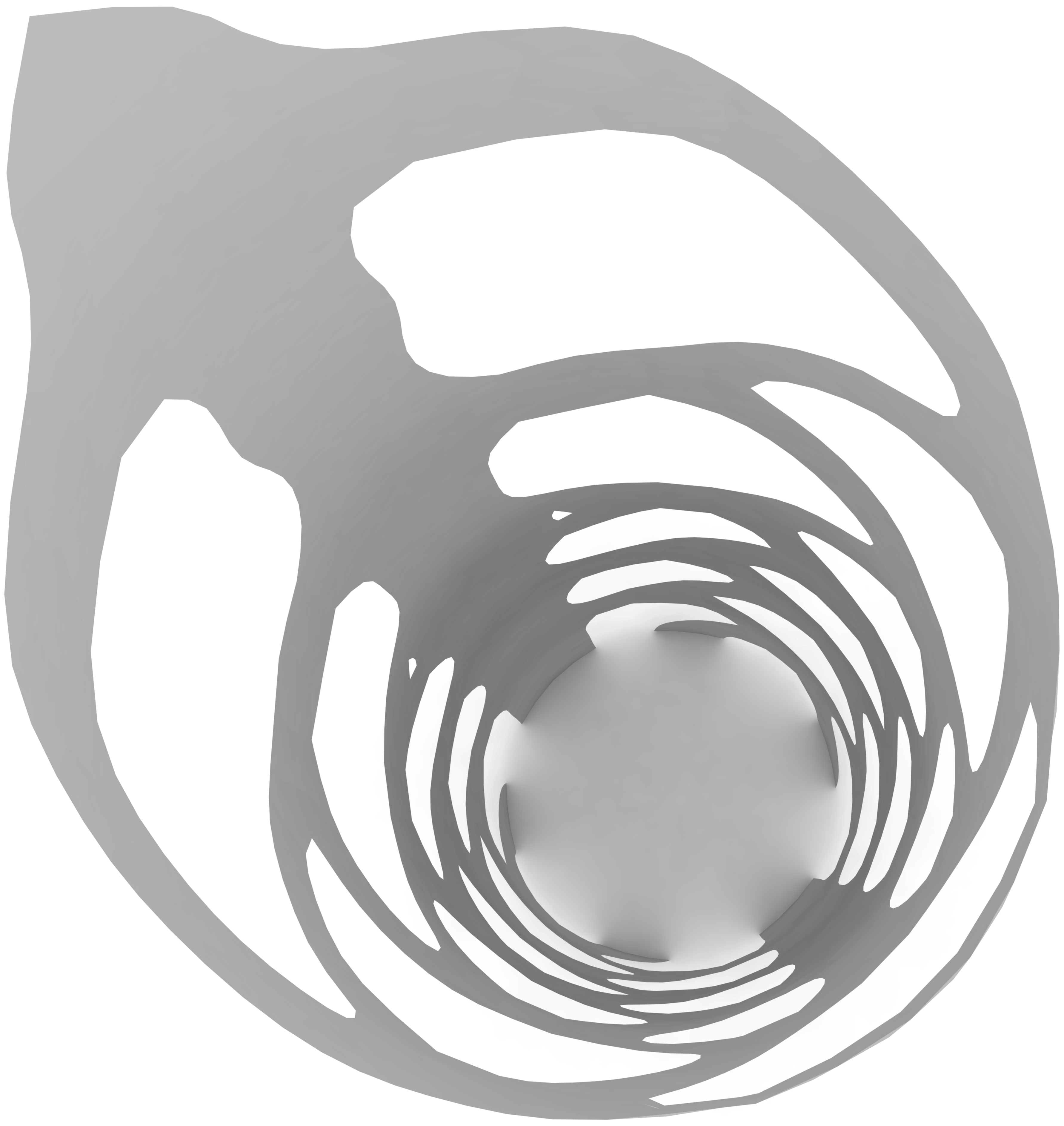
The studies described here deal with examples of natural structures, including cactus skeletons, bones, and diatomeea. Further studies not displayed here include structural studes of the Nautilus shell, branched strucutres and the supporting structure of the dragonfly wing. They include the description of their fundamental structural behaviour, the generation of digital structural models and the study of optimization procedures. As a conclusion, the analysis and understanding of natural structures using modern tools of formfinding and optimization may lead to new optimized structures using modern design tools.

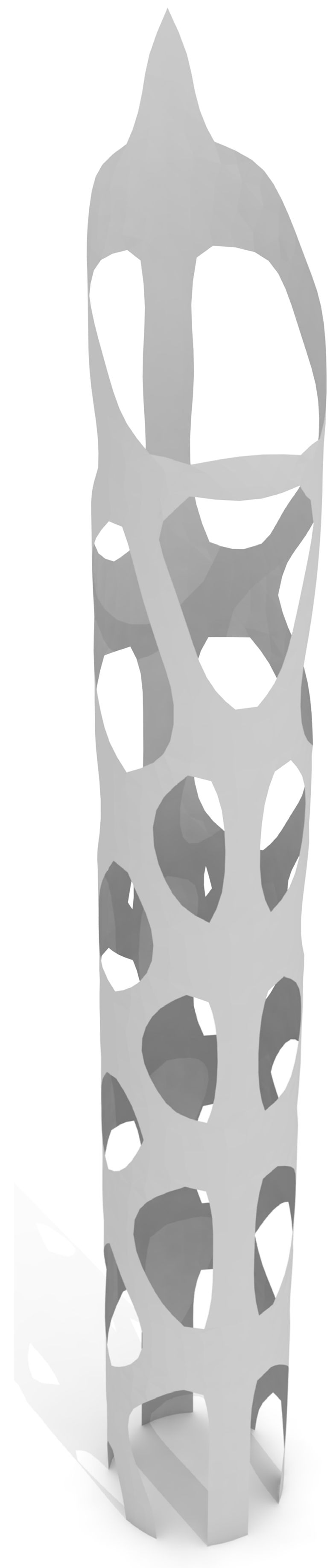
Procedure

The shape studies carried out use FEM software package Altair HyperWorks / OptiStruct including features for structural optimization.
When performing studies of structural optimization, the generation of the finite element model of the structure, with a refinement of the meshing in dependence of calculation times and model accuracy, is the first step. The objective function and side constraints are defined and the optimization is started. For the optimization studies carried out in these studies, the optimization goal is the minimization of the structural compliance. The optimization algorithm will then search for a structure with maximum stiffness. In order to avoid the optimization algorithm to fill up the whole design area with material, a material or volume fraction needs to be defined, usually described as a percentage of volume of the design space.
Once the optimization has converged, the „design proposal“ with density values between 0 („no material“) and 1 („full material“) is displayed. The term „design proposal“ indicates that the optimization result, just like basically every finite element calculation, is an approximation: it needs interpretation and further studies in order to be developed into an actual structure. At the same time, the design proposal is connected to the value of the objective function (e. g. compliance of the structure; amount of material needed) that was achieved by the optimization algorithm, therefore enabling the designer to directly evaluate the geometry generated.

Studies in structural optimization produce very aesthetic, often organic, mostly very delicate structures. Performing optimization studies is a valuable tool in the structural design process: the connection of the design proposal (visual) and the performance (numerical) helps in taking decisions and in straightening the often diverging influences of the design process.

The studies were content of a study in the Master Class at Biberach University of Applied Sciences, winter term 2011-12.
Preliminary studies: Marianne Bolmer, Pinar Ciftci, Michael Ettwein, Vincent Hendricks, Eva Kienle, Aysel May, Fabian Prix, Jürgen Rölle, Michael Schwarz.
Optimization models: Irmgard Lochner
Visualizations: Vincent Hendricks (3), Jürgen Rölle (1).



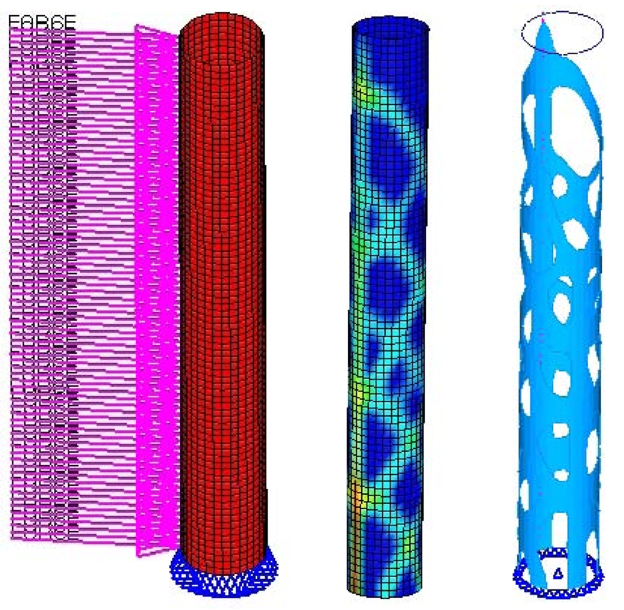


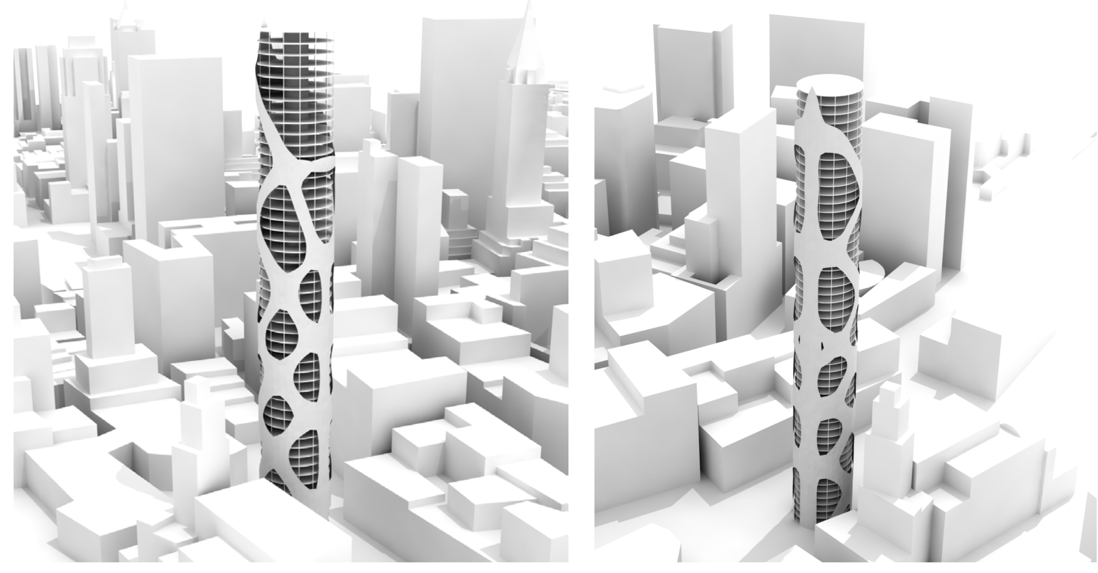
The columniform cactus: an optimized cantilever

The columniform cactus reaches up to approximately 6 m of height. It is a vertical cantilever with a very efficient structure, referred to by Frei Otto as an example for an optimized natural strucutre. Its "skeleton“ can be described as a perforated tube structure. Developed by the SOM-affiliated engineer Fazlur Khan in the 1960s, tube structures are very efficient structural systems for the design of tall slender buildings. The concentration of material along the outline of the structure allows for optimized structural efficiency in comparison to the classical core structure.

The cactus skeleton structure concentrates load-bearing material in a certain geometry that resembles natural as well as technical structures. The physical finite element model consists of a cast-in tube under horizontal loading.

Applying this geometry study to the design of a slender high-rise building, a "tube-in-tube-structure" can be futherly developed. It encounters that the optimization is carried out for only one form defining load case - here: the pre-dominant wind direction. An additional inner tube - as it was also proclaimed by Fazlur Khan - can cover deviating load cases on the one hand and support the very much "thinned out" top parts of the structure. As a result, an aesthetic and efficient structure is developed.



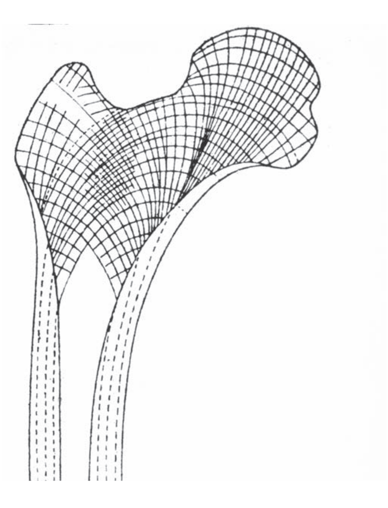


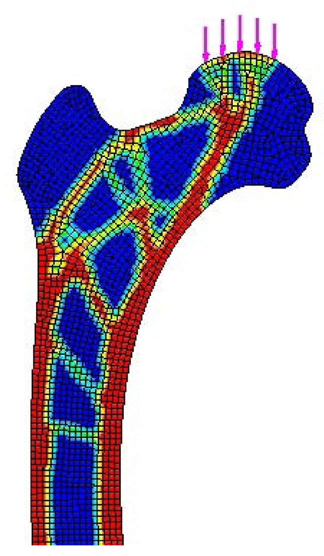
Bone structures: pinching and homogenization

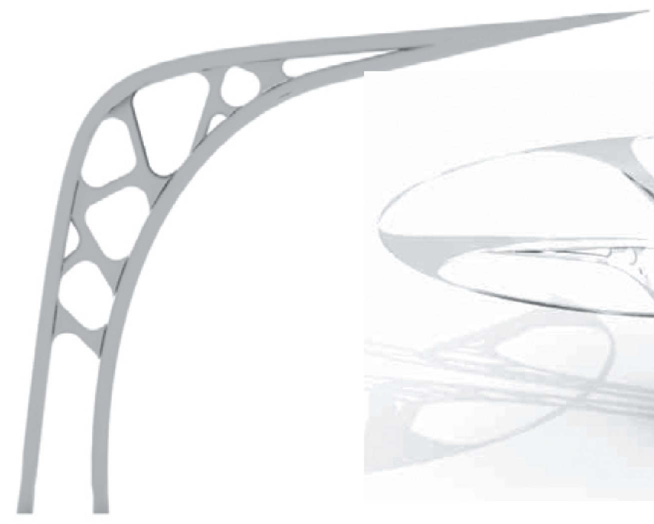
Load paths, trajectories, efficient structures, ... many times, the microscopic geometry of bone structures is referenced to as an example of an optimized structure, developed by natural evolutionary optimization over decades. In fact, the geometry of the spongiosa of the thigh bone can be directly related to principal stresses within a continuum.

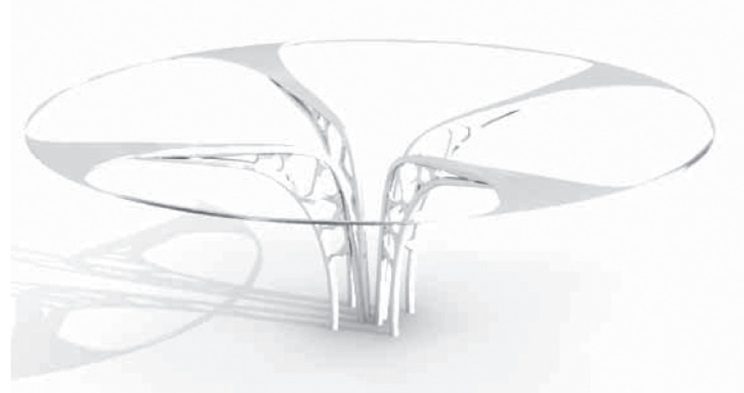
Simulating this stress condition - an excentrally loaded cast-in column - produces as a design proposal a truss structure, leading into a structure of pure bending where structural material is concentrated along the bending axis. Material is "pinched" where it is not efficient - a very typical process in the development of natural lightweight structures.

Transforming this design idea into a project task, a cast-in cantilever structure can be developed with a global geometry on the one hand - structural height increasing towards the cast-in supports - and a micro-geometry on the other hand - deriving the truss structure in reference to the structural behaviour and geometry of natural bone structures.









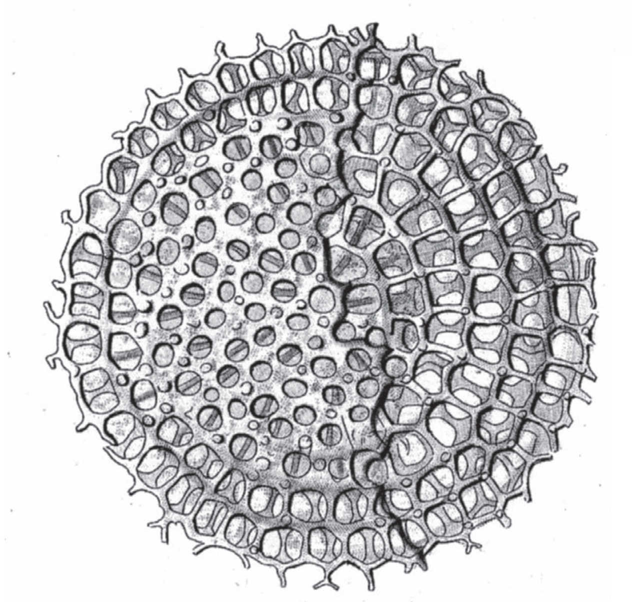
Shell shape and topology

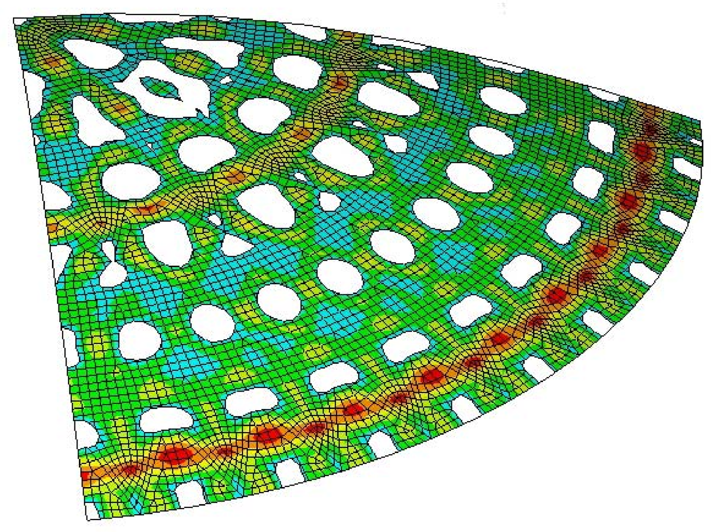
The species of diatoms have been keeping biologists and engineers busy for a long time. Until today, there exists an evolutionary competition between the stronger crab and the corresponding shell...

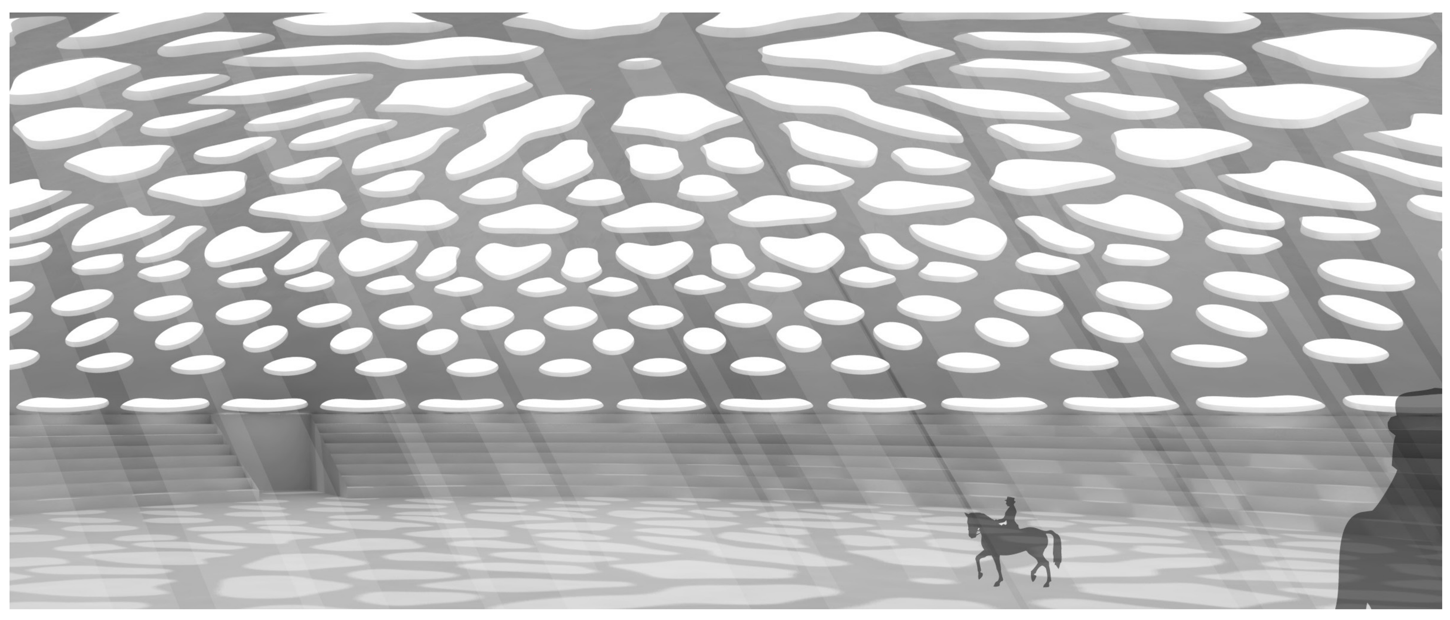
Ernst Haeckel is one of the pioneers to demonstrate the amazing variety of shapes in microcosmic structures - with descriptive variations of structural shapes depending on the overall geometry as well as on the loading conditions of a structure.

The division into "Centrales" with radial geometries and "Pennales" with bilaterally symmetric shapes leads to an overall classification of diatom geometries. When carrying out studies of structural optimization, these geometrical influences have to be taken into account - as it can be seen from a comparative optimization study of a circular geometry compared to an elongated geometry.

The "design proposals" produced by the optimization algorithm refer directily to the loading and geometrical conditions of the design project. This can be developed into the design of shell structures with varying global geometries.







Shells under pressure: shape and performance

The bone structure of sea urchins confronts us with several structural questions. On the one hand, the sea urchin can be classified as an echinoderm - which segments into a whole diversity of shapes. Furthermore, there are several species with different geometries that depend on the configuration of spikes, which are partially movable, therefore influencing the reinforcement of the bone structure.

The overall geometry of the sea urchin shell is therefore derived from the inner pressure, the outer pressure and from the support conditions given by the spike footings. Frei Otto formulated the description of the sea urchin as a pneumatic structure - taking into account loading conditions from outside as well as from inside, and especially considering single point supports.

Shape studies of sea urchins can therefore consider a wide range of structural systems. In the study carried out here, a given shell topology was subject to outer pressure and optimized with a given material range. The optimization procedure results in an optimized grid shell geometry, following the global shell geometry and developing a local grid shell layout correspondingly.

The design proposal could be developed into the design of an underwater shell - serving for example as an observatory in the deep sea.