Form-Optimizing in Biological Structures

The Morphology of Seashells

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1. INTRODUCTION

Henry Moseley [1] started in 1838 the study of seashells and in particular the mathematical relationship that controls the overall geometry of shells. He was followed by many researchers such as Thompson [2], Raup [3, 4], Cortie [5], and Dawkins [6] and others. The shape of seashells is caused by a logarithmic natural growth *(Fig. 4-5)*. There are three basic shapes: the Planispirally coiled shell *(Fig.1)*, the Helically coiled shell *(Fig.2)*, and the Bi-valve shell *(Fig.3)*.

Environmental factors such as the availability of raw materials, the type of substrate, the amount of calcium present, as well as many other factors contribute to deviations from the three basic forms.

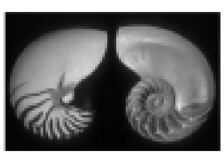
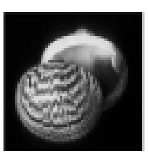




Fig. 1 Planispirally Coiled Shell (Wye p.277). Fig. 2 Helically Coiled Shell (Harasewych p.162). Fig. 3 Bi-Valve Shell (Wye p. 243).

2. GROWTH

Increases in height greatly benefit shells. It allows for greater tissue volume and more capacious mantle cavities, which in turn provide space for larger and more elaborate mantle cavity organs. The downside for the increase in height is the shift of the center of gravity making the shell very unstable for the animalinhabiting it. Not only is coiling a great solution to this problem, it also maintains constant shellproportions. Examples of shells that conform to some portion of a logarithmic spiral can be found in all classes of single-shelled mollusks.

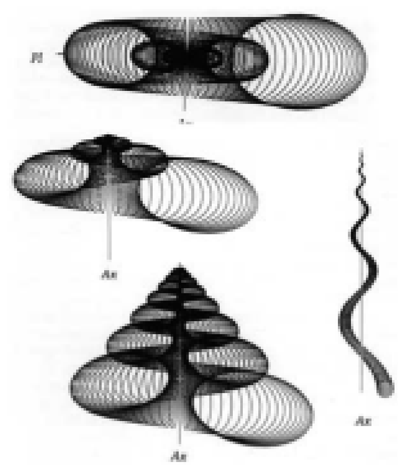


Fig. 4 - Computer simulation of one valve of the bi-valve Meiocardia moltkiana (Harasewych p.17).

3. SEASHELL GEOMETRY

The seashell geometry can be expressed by four basic parameters [Raup]. As shown in Figure 6, A is the shape of the aperture or the shape of shell section, B is the distance from the coiling axis to the center of the shell section, C is the section radius, and D is the vertical distance between sections. The columella is the elongated cone around the coiling axis, the internal structural support of the shell. The suture line is the intersection of the sections vertically. The columella and the suture line are the result of the spiral growth of the seashell.

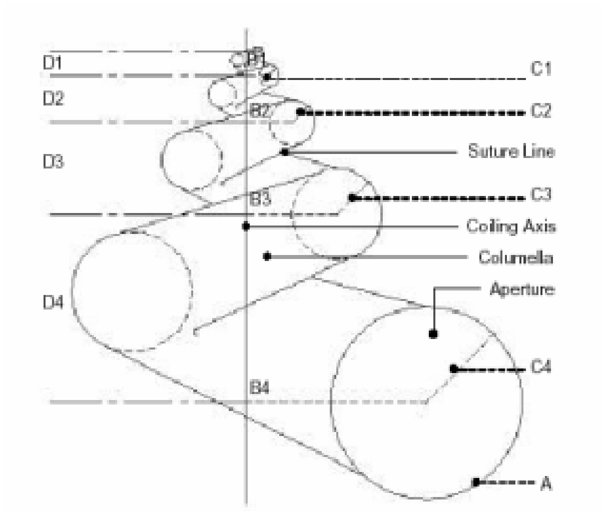
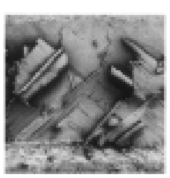


Fig. 5 - Computer simulation of a planispirally coiled shell and of three helically coiled gastropod shells (Harasewych p.17).

4. FORMATION OF THE SHELL

All mollusks have a mantle. This is a specialized secretory region on the animal's upper surface. Itproduces a thin, flexible covering or cuticle make of a specialized protein known as conchiolin. All mollusk mantles also contain unique cells that secrete a fluid from which the various forms of calcium carbonate can be crystallized. Crystallization occurs along the inner surface of the conchiolin, creating a continuously mineralized shell. The molluscan shell, a complex structure composed of mineral and organic components, forms outside of the animal's tissues.



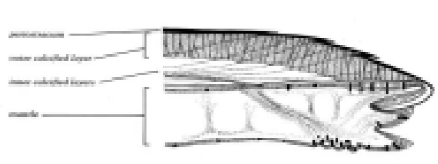


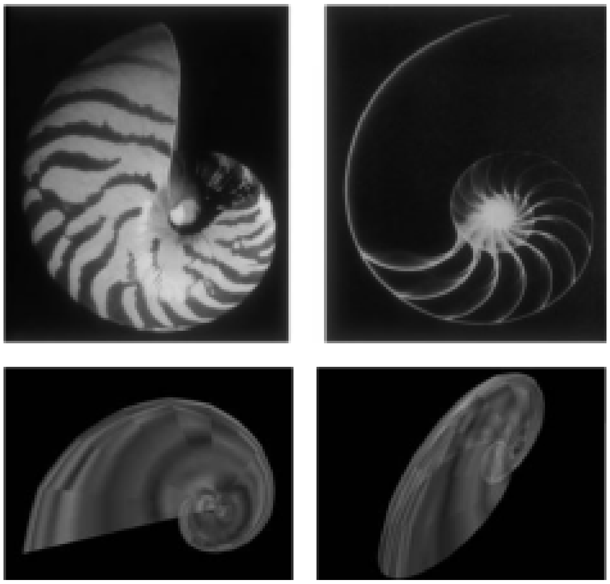
Fig. 6 - An electron microscope photograph of the shell of Busycon carica broken parallel to the edge of the shell. Three different
crystal layers can be seen (Harasewych p.16).
Fig. 7 - A cross-sectional view of the mantle and shell at the growing edge of a bi-valve (Harasewych p.16).

The molluscan shell contains multiple layers that vary in thickness, crystalline form and orientation. Adjacent layers are often deposited with their crystal planes at right angles to each other, resembling the pattern seen in plywood.

This dramatically increases the strength of the shell. Most shells consist of three major components, each produced by a different region of the mantle. The outer most protein layer is added along the edge of the shell by a specialized region of the adjacent mantle edge. Next, an outer calcified layer is underneath. The inner calcified layers follow, and finally, the largest region is the mantle. An unavoidable consequence of this type of calcification, common to all shelled mollusks, is that growth can only happen by the addition ofmaterial to the shell edge. Once formed, the shell cannot be modified except for its internal layers. Thiscreates limitations on the general architecture of the shells.

5. DIGITAL MODELING

The three basic seashell shapes, the Planispirally coiled shell *(Fig.1)*, the Helically coiled shell *(Fig.2)*, and the Bi-valve shell *(Fig.3)* can be reconstructed in a digital model as a variation of the mathematical relationship between the four parameters: 1. The shape of the aperture / shell section. 2. The distance from the coiling axis to the center of the shell section. 3. The section radius. 4. The vertical distance between sections. The result of a specific mathematical combination reflects the shell form for specific seashell specie.



Planispirally coiled shell

Nautilus Planispirally

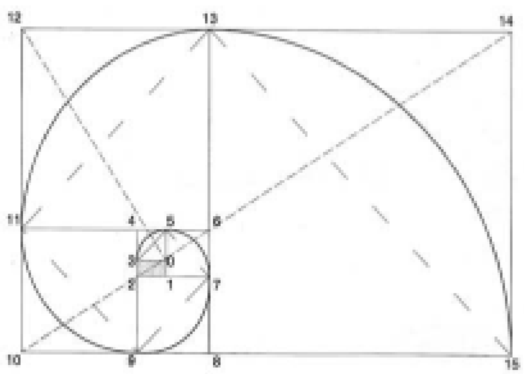


Fig. 8 - Elevation and x-ray view of Chambered Nautilus (Conklin p.189).
Fig. 9 - Diagram of proportioning system of planispirally coiled shell.

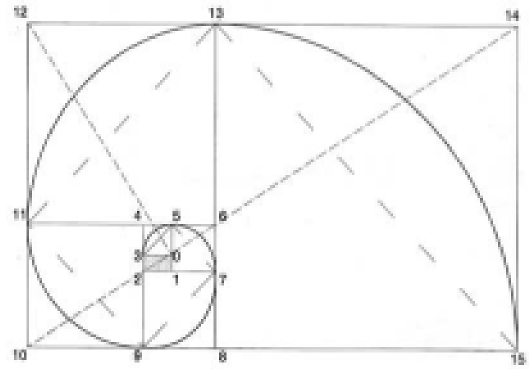


Fig.10 - Computer wire frame model of nautilus planispirally coiled shell.

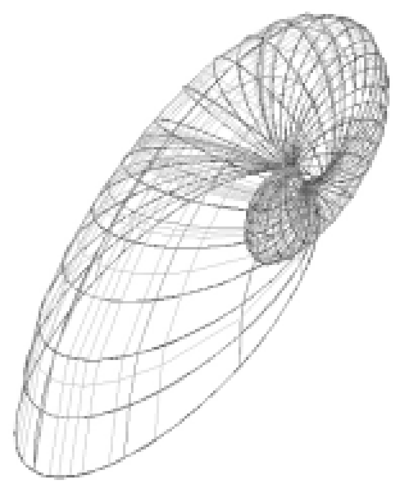
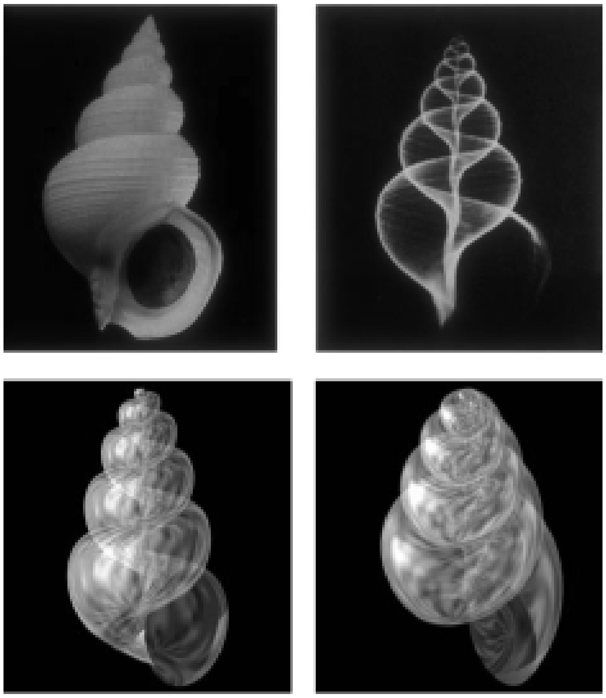


Fig. 11- Rendered computer model of nautilus planispirally coiled shell.



HELICALLY COILED GASTROPOD SHELL

Fig. 12 – Elevation and x-ray view of helically coiled gastropod shell (Conklin p.45).
Fig. 13 – Diagram of proportioning system of helically coiled gastropod shells.

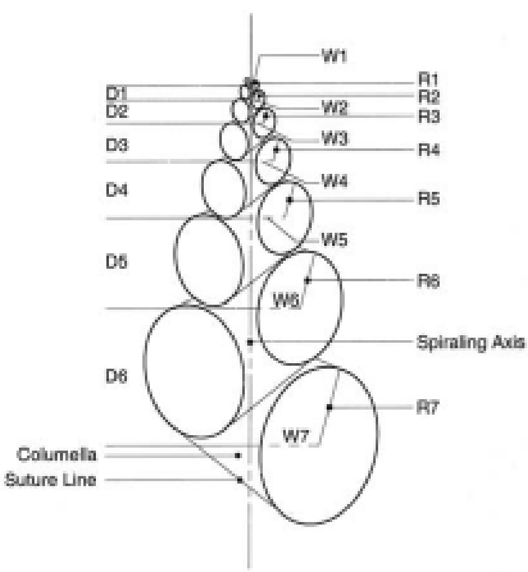


Fig. 14 – Computer wire frame model of helically coiled gastropod shells

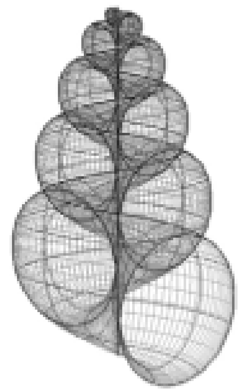


Fig. 15 – Rendered computer model of helically coiled gastropod shells.

HELICALLY COILED GASTROPOD SHELL

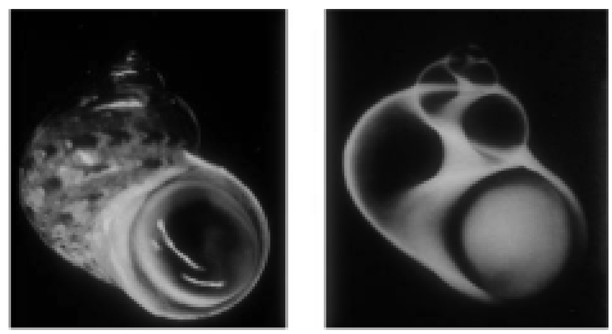


Fig. 16 – Elevation and x-ray views of helically coiled gastropod shell (Conklin p.153).

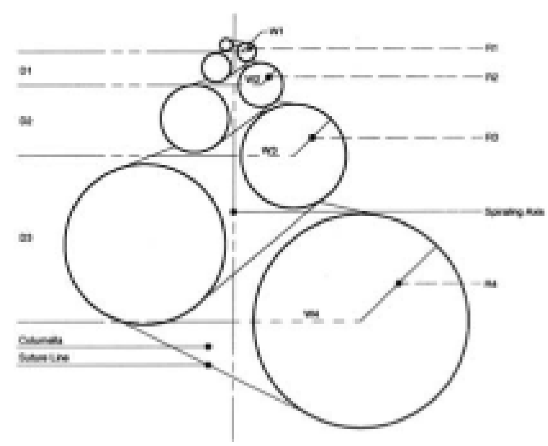
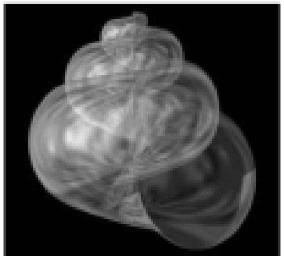


Fig. 17 - Diagram of proportioning system of helically coiled gastropod shells.



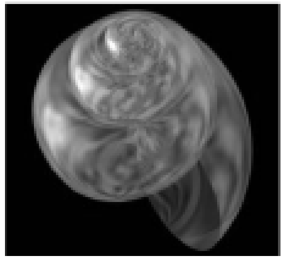
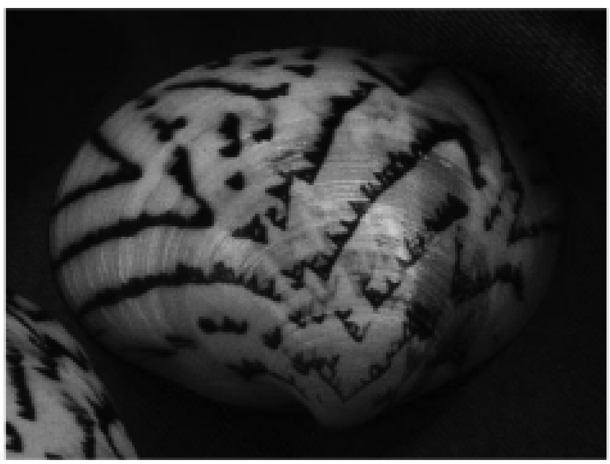
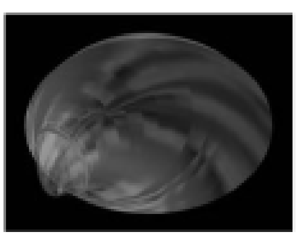


Fig. 18 – Computer wire frame model of helically coiled gastropod shells
Fig. 19 – Rendered computer model of helically coiled gastropod shells.



BI-VALVE SHELL

Fig. 20 – View of Bi-Valve Shell (Harasewych p.209).



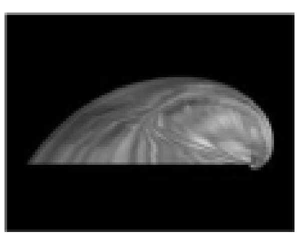


Fig. 21 – Elevation of computer wire frame model showing exponential curve of shell growth.
Fig. 22 – Three dimensional representation of proportioning system used to develop curvature bi-valve shell.

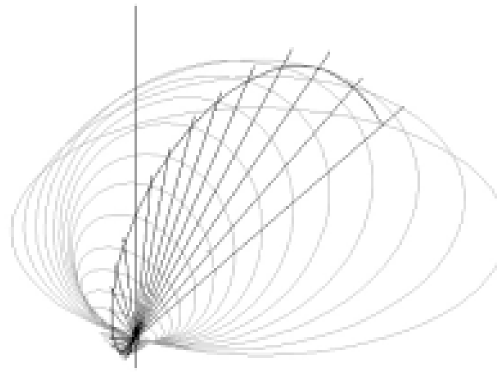


Fig. 23 – Computer wire frame model of of bi-valve shell.

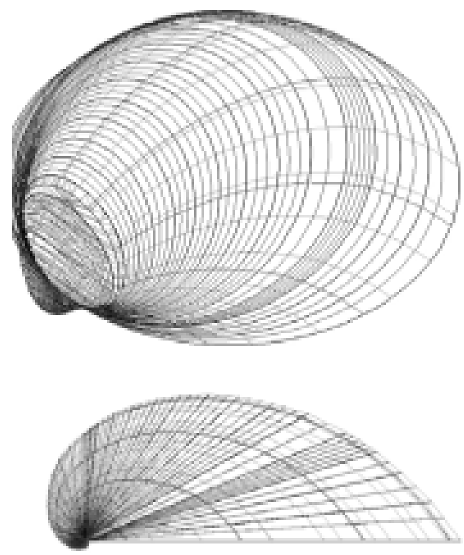
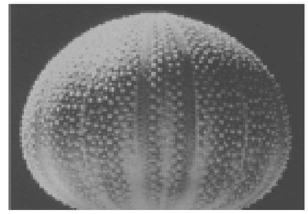
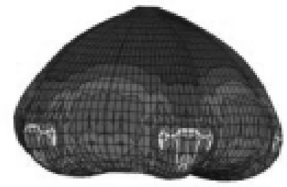


Fig. 24 – Rendered computer model of bi-valve shell.

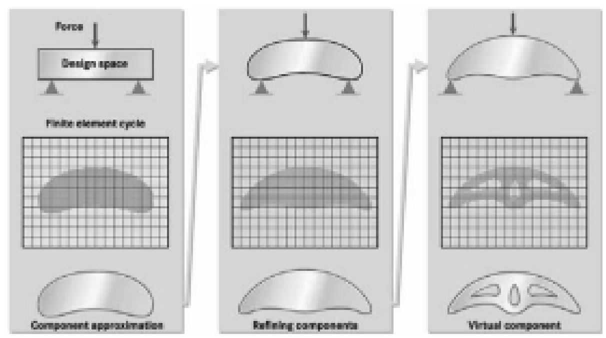
6. STRUCTURAL OPTIMIZATION IN ENGINEERING - SEASHELL STRUCTURAL PROPERTIES

The shell geometry responses to any external and internal loads by redirecting forces within a very thin section of shell structure along its natural multiple curvatures. Finally these forces are transferred to the supported area such as ground, rock or sand depending upon how the seashell positions itself in the environment.





(Fig. 25) Structure optimization in the shell structure of a sea urchin
(Fig. 26) Finite Element analysisii of sea urchin shell, color coded stress analysis [8 Process und Form*, K. Teichmann]*



(Fig.27) SKO method (Soft Kill Option). [9 HIGHTECH REPORT 1/2003, pp60-63]

Genetic algorithms

In engineering fields, accomplishing an objective with a minimum of effort, either in terms of material, time or other expense, is a basic activity. For this reason it is easy to understand the interest designers have in different optimization techniques like the seashell structure. Mathematical, as well as, model based tools have traditionally been employed for such optimization. In recent times, mathematical methods executed on computers have become predominant. Unfortunately, computer derived solutions often obscure the range of possible solutions from the designer by only exhibiting a final, 'best' solution. Naturally, optimization methods can only respond to the objective parameters which are coded into the problem, and as a result, non-coded parameters, such as aesthetics, or context are left out of the optimization process, and ultimately left out of the final design solution.

Structural optimization in engineering takes natural constructions as an example. Similar to nature itself, computer-generated genetic algorithmsi can be calculated using stated goals to achieve global optimization - the search strategy is, like in nature, goal-oriented. An evolutionary algorithm maintains a population of structures (usually randomly generated initially), that evolves according to rules of selection, recombination, mutation and survival, referred to as genetic operators. A shared 'environment' determines the fitness or performance of each individual in the population. The fittest individuals are more likely to be selected for reproduction (retention or duplication), while recombination and mutation modifies those individuals, yielding potentially superior ones. Using algorithms, mechanical selection, mutation and recombination improves generationally with a fixed parameter size and quality.

COMPUTER-COMPRESSED EVOLUTION

Design space and finite elements

Computer-compressed evolution like the SKO method (Soft Kill Option) (Fig.27) follows the sameconstruction principle that nature employs to promote for example the shell growth of a sea urchin (fig.25/26) or the silica structure of sea shell (Fig.1/3). Building material can be removed wherever there are no stresses, but additional material must be used where the stresses are greater. This is the simple principle that evolution has used for millions of years to produces weight optimized 'components'. Using computer programs based on computer-generated genetic algorithms like the SKO methodiii, scientists are now able to simulate this evolution and compress it into a short time span. [9]

In order to simulate lightweight engineering strategy according to nature's guidelines, scientists using the SKO method must first define a virtual design space, which represents the outermost parameters of the component being developed (Fig.27). To subdivide this design space into many small individual parts, the finite elements, a grid is applied. If now a virtually external load applied, the computer calculates the resulting force exerted on every one of the finite elements. The FE model shows exactly where there is no load stress on a component and in turn shows where it is possible to make savings with regard to the materials used. On the other hand, for areas that bear heavy stress the simulation program indicates the need to reinforce the construction material. Like nature the computer repeats this 'finite element cycle' several times. As a result, they can refine a component repeatedly until the optimal form — one that evenly distributes the stresses within a component — is found.

CONCLUSION

The abstract geometrical properties of seashells can be described by there mathematical relationship. The translation of abstracted nature in mathematical terms and by applying prerequisite architectural considerations is the fundamental concept of form and structure analyses. The value of this research is to develop mathematically definable models of structure systems in nature. The goal is to define a set of structural principles, and to make those principles applicable for architects and engineers.

Seashell structures are perfect study models for self- organization structures in nature because of their relatively simple physical and morphological principle and geometry based on four basic mathematicalparameters. Self-organization it the defining principle of nature. It defines things as simple as a raindrop or as complex as living cell - simply a result of physical laws or directives that are implicit in the material itself. It is a process by which atoms, molecules, molecular structures and constructive elements create ordered and functional entities.

Engineers are using this concept already successful for optimization processes in a white range of applications starting in mechanical-, medicine-, air and space engineering. Architects are only one step away adopting the same technique for designing in a macro scale buildings and structures. Material scientistsiv are already designing and producing new materials or smart materials in a Micro scale using the self organizing principles. In the future, the material engineers will develop constructions out of selfstructuring materials that consciously use the principles of self-organization, creating not only materials with brand new properties but also inspiring architects to define their constructions in a more intelligent way.

At its best, intelligent structures and materials will influence the entire philosophy of construction. Engineers will no longer ensure safety through quantity of material and cost. Simple structural analysis will no longer suffice; instead, self-organizing structures will define the new construction principles.

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i A genetic algorithm generates each individual from some encoded form known as a ‘chromosome’ and it is these which are combined or mutated to breed new individuals. The basis for the optimization is a vast array of possible solutions (population), where every solution (individual) is defined through a particular parameter (chromosome). The individuals within a generation are in competition with one another (selection), in other words, the value (fitness) of the individual is what allows the survival of the parameter (gene) until the next generation. The results of this computer-supported process are automatically generated and optimized.

Evolutionary computation is useful for optimization when other techniques such as gradient descent or direct, analytical discovery are not possible. Combinatory and real-valued function optimization in which the optimization surface or fitness landscape is ‘rugged’, possessing many locally optimal solutions, are well suited for evolutionary algorithms. Professor Dr. Bucher, Institute für Strukturmechanik at the Bauhaus University Weimar, Germany developed the program Slang.

ii The finite-element-method is a procedure used to solve structural-mechanical calculations with precedence given to the threedimensionality of the system. As a result, the construction is broken into discreet elements - Finite Elements (FE) – such as columns,beams, plates, shells, etc. characterized by the individual connections (discreet points) where they are combined with one another.

iii The DaimlerChrysler Reaserch Center Ulm and Uni Karlsruhe, Prof. Claus Mattheck, in Germany developed the SKO method (Soft Kill Option). The method is based on the idea that is it only possible to achieve a combination of the lightweight and maximum strength in a design when the stresses are constant over the structure’s entire surface area, ensuring that no area is under- or overstressed.

iv Saarbrückener Institut für Neuer Materialien [INM], Frauenhofer Institute für Fertigungsmechanik und Angewandte Forschung,

Bremen