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PARAMETRIC OPTIMIZATION OF LIGHTWEIGHT STRUCTURES

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Abstract. The building and operation of buildings consumes a significant proportion of the available energy resources and raw materials around the world. For this reason, continued research is being conducted into ways and means of making more efficient use of energy and resource consumption in constructions, both in terms of the form and topology of structures as well as the improvement and development of new building methods and adaptable, smart materials. At the same time, architects are increasingly employing a more freeform architectural language. Although these may at first glance seem like contradictory tendencies, they can in fact be addressed very effectively using parametric models and tools, especially in the early design stages, opening up new ways of planning energy-efficient structures that make economic use of resources.

1 INTRODUCTION

The development of lightweight wide-span structures has always been an area of special fascination for architects and engineers. A typical means of bridging large spans is to use shell structures. These structures have traditionally been optimized using analog form-finding processes such as that shown in fig. 1 and, when an optimum membrane stress is reached, can be realized using skins of minimal section thickness. These form-finding processes have since evolved from the experimental procedures used in the past to highly complex numerical methods.

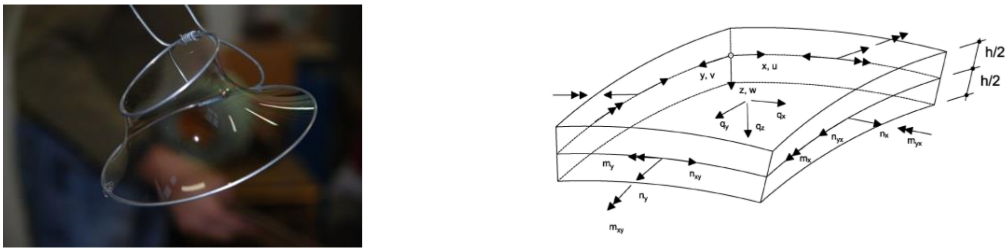


Figure 1: Left: soap-skin model; right: illustration of a shallow shell [1]

The design of shell structures needs to unite the need to achieve an optimal distribution of forces within the shell with the desire for a functional and distinctive form. To assist in the design and modeling of freeform shell structures, parametric modeling tools are increasingly being used which enable powerful parametric calculation methods to be controlled using innovative interfaces. This makes it possible to generate the finite-element-model directly from the parametric geometry model and in turn to automate the calculation and optimization processes.

As planning processes have to be completed in ever shorter timespans, it becomes increasingly important to be able to explore a variety of potential options and their feasibility during the early stages of the design process, as the design decisions made here influence the rest of the construction process (see fig. 2).

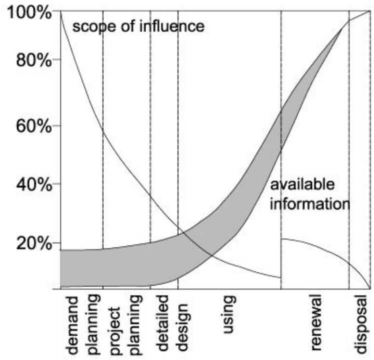


Figure 2: Development of project information during planning [2]

In addition to designing an optimal outer form for the shell, it is also possible to optimize the inner structure of the materials, for example, the fiber orientation of reinforced composites can be arranged to benefit the flow of forces. In addition to modeling the behavior of conventional passive fibers, smart materials with active fibers can also be considered. The properties of smart materials vary widely with respect to the strains and stresses they can sustain, and it is therefore necessary to evaluate which smart materials are suitable for the respective construction task (see fig. 3). The most common smart materials are piezoelectric ceramics, shape memory alloys and magnetostrictive ceramics.

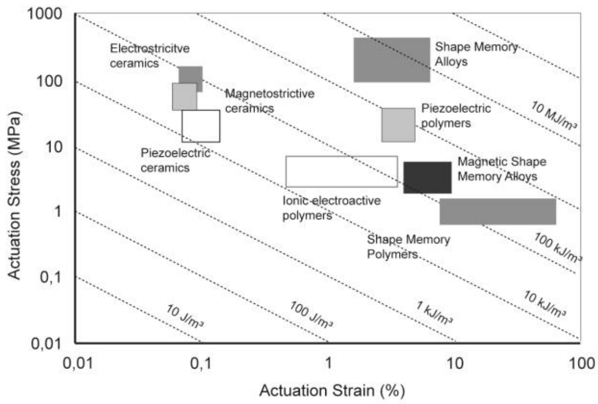


Figure 3: Stress-strain diagram of smart materials [3]

2 PARAMETRIC OPTIMIZATION OF FREEFORM SHELL STRUCTURES

2.1 Parametric tools and holistic optimization modules

The use of parametric design tools in architectural design is becoming increasingly widespread. Examples of parametric design programs include GenerativeComponents by Bentley Systems and the CAD application Rhinoceros3D in conjunction with the parametric programming interface Grasshopper by Robert McNeel & Associates. Parametric modeling tools facilitate the generation of geometric models using a set of variable parameters. As such, data is not stored in the form of rigid geometries; instead the geometries are attributed to their original elements, e.g. node, line and surface, and the data is stored in the form of descriptive coordinates (x, y, and z) and further linking dependencies [4]. The primary advantage of this approach is that the geometry is defined by a set of parameters and can adapt automatically to reflect any adjustment the designer may make to the design parameters or requirements.

Figure 4 (top) illustrates the principle of parametric geometry modeling. The generated geometries are described by basic geometrical definitions. This level of information is ideally suited for directly linking parametric geometry and parametric calculation models. The link itself is controlled by an appropriate interface, which can be defined and customized using the open software architecture of programs such as Grasshopper. In addition, parametrically addressable structural calculation programs are also needed. These programs must be able to process text-based calculation files and need to be scriptable so that they can be addressed with commands from the command line. One example in this context is the finite element program system SOFiSTiK with its embedded input language CADINP.

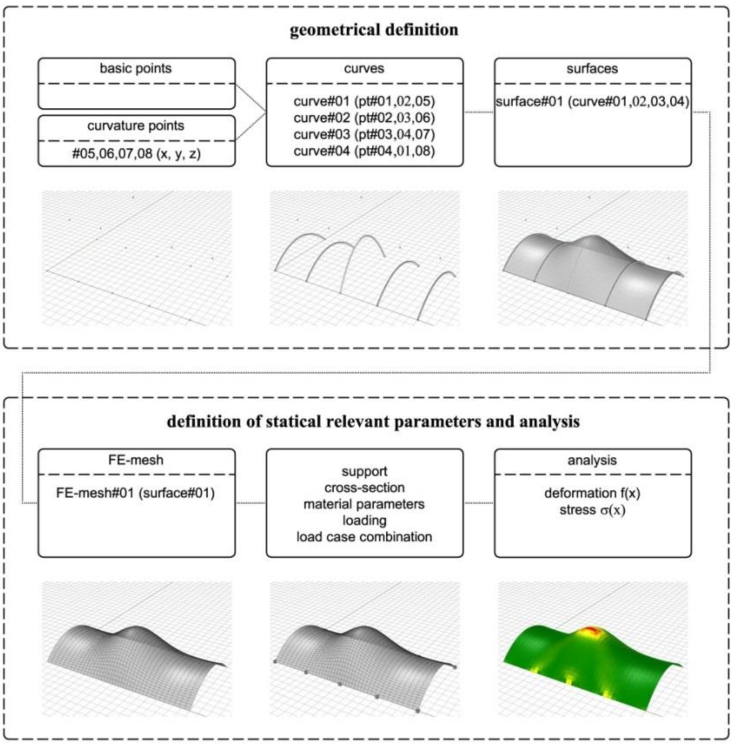


Figure 4: Parametric tools for geometry definition and analysis [5]

Figure 4 (bottom) shows an example of the transfer of a parametric geometry model to a parametric analysis model. The extension of the geometry model essentially comprises the transfer of point coordinates into structural nodes, of lines into beams or columns and of surfaces into finite-elements. Furthermore the definition of loads, load cases, load combinations, material parameters and section properties is necessary. When using SOFiSTiK, all the aforementioned information is stored in a closed text-based calculation file. This file needs to correspond to the logic and syntax of the Finite-Element software used (e.g. CADINP). This procedure makes it possible to generate all the information needed for calculation directly in the parametric programming interface. To this end, we developed a module entitled StructureDataTranformator (SDT) that facilitates the automated transfer of data between the parametric programming tool Grasshopper and SOFiSTiK (see fig. 5). The parametric programming interface outsources the calculation to the addressed SOFiSTiK-routines. By using this module it is possible to calculate individual files as well as to batch process several files. The results of the individual calculations are stored in a special database. Relevant information is read from the project database and translated into generally readable data formats (*.txt, *.xls). Using our SDT interface, necessary information can be transferred back to the parametric programming interface in Grasshopper making it possible to determine any necessary shape changes to reduce stresses or deformations in the geometry analysis. All the results, such as the geometrical information, can be provided as vectors for subsequent use. For example, the complete analyzed geometry can be used directly by other planning partners for their respective investigations without the need for any complex remodeling.

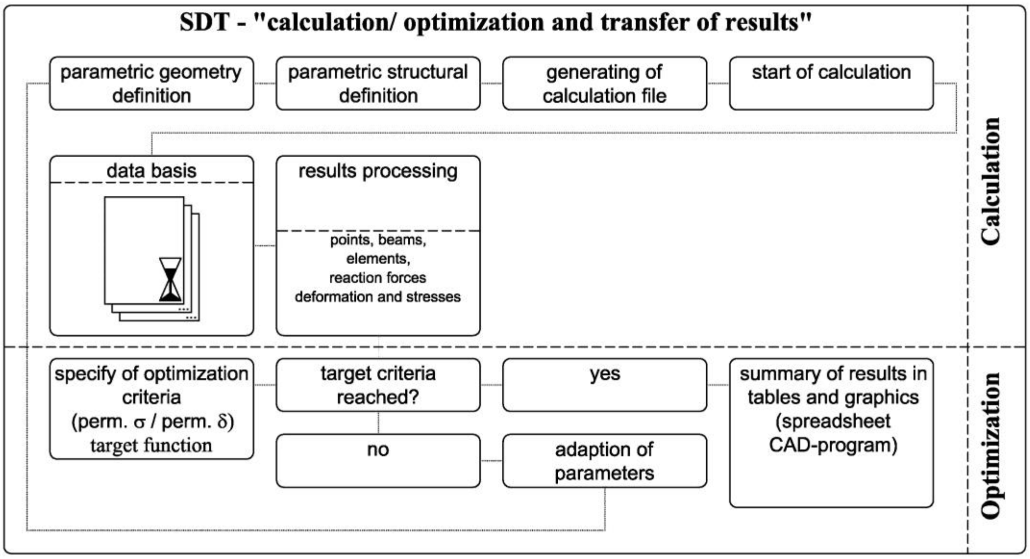


Figure 5: SDT – calculation / optimization and transfer of results [5]

2.2 Evolutionary optimization in structural design

The goal of sustainable structural engineering is to find an optimal design for all structural aspects. Automated optimization algorithms are particularly useful for the planning of complex freeform structures. The use of evolutionary algorithms is particularly suitable when meaningful solutions cannot be achieved using conventional algorithms [6]. Figure 6 shows an overview of various different approaches to evolutionary algorithms [7] which have been developed simultaneously by different authors.

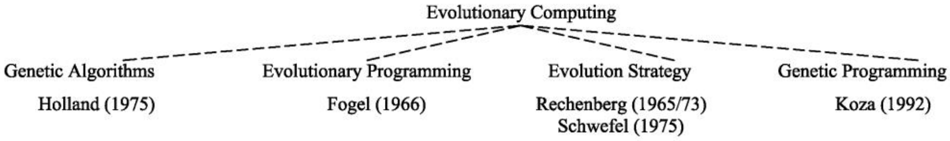


Figure 6: Chronological overview of evolutionary algorithms, adapted illustration by [7]

Evolutionary algorithms are mathematical algorithms that attempt to emulate natural evolution patterns. Their key parameters are selection, recombination and mutation [8]. During optimization, a range of different individuals are generated and then checked with respect to how well they fit the optimization goal. They are then either fed back to the optimization process as a new starting genome or are eliminated. Figure 7 illustrates the basic expiration cycle of an evolutionary optimization.

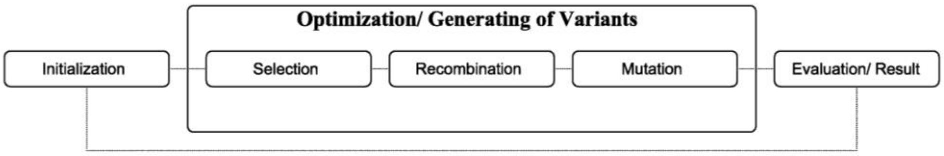


Figure 7: Expiration of an evolutionary optimization [9]

The direct link between both the geometry model and the calculation model is particularly useful in combination with an evolutionary algorithm. The parametric algorithmic editor Grasshopper supports the application of different optimization routines (e.g. Galapagos, Goat, Octopus). The integration of evolutionary optimization algorithms into the parametric geometry and calculation model makes it possible to optimize and analyze multiple individual variants. Each individual variant is evaluated with respect to a specified objective function (fitness criteria) and the structure then modified as necessary by altering the variable parameters to generate new structural variants. The direct link between the optimization tool, the geometry model and the computational model makes it possible to perform continuous optimization, a prerequisite for gradual evolutionary optimization. The optimization process stops automatically once the objective criterion is achieved or after a predefined number of iterations or a certain duration.

The user must nevertheless critically assess the results of the optimization process because not every solution corresponds to a global maximum or minimum (see fig. 8).

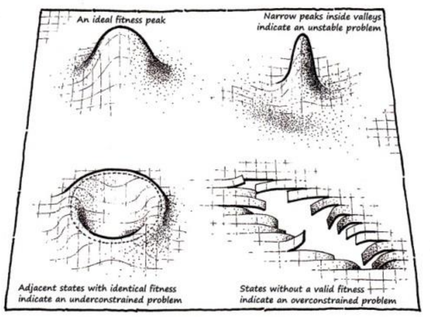


Figure 8: Representation of a fitness landscape [10]

3 INTEGRATION OF ADAPTIVE FIBERS

Material optimization is a further means of improving the performance of filigree shell structures. Nature provides a number of examples of high-performance material compositions: in locusts, for example, the dorsal plate that shields the thorax and the tendons of the legs have different internal structures that are optimally adapted to the loads they sustain [11, 12]. The tendons exhibit a parallel arrangement of fiber bundles that correspond to the normal forces that occur (tension). By contrast, the material structure of the dorsal plate features a multilayered arrangement of fibers to resist the shear forces that act on it (see fig. 9).

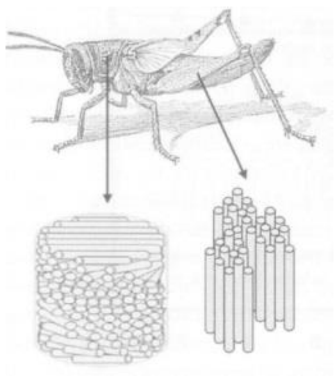
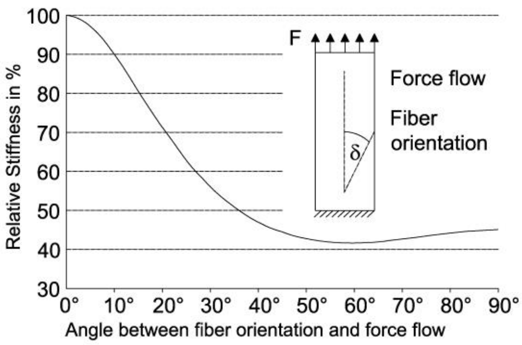


Figure 9: Chitin fiber structure of a grasshopper [11]

The transfer of such knowledge from the natural world to technical structures is known as bionics or biomimetics. In the field of technical fiber composites, significant advantages can be achieved by arranging fibers affine to the load. Figure 10 (left) illustrates the relationship between fiber orientation and the stiffness of a fiber composite. Where the angle between the fiber orientation and the direction of the load exceeds 50°, the stiffness decreases by 60%. Where various forces act on a structural component, a multilayer arrangement of fibers in several different directions is beneficial (see fig. 10, right).



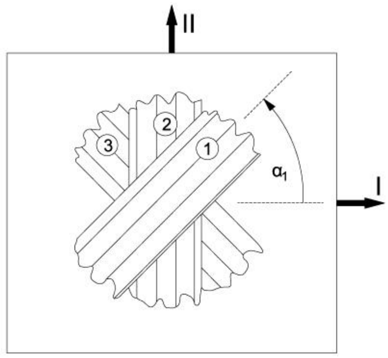


Figure 10: Left: relationship between fiber orientation and stiffness [13]; right: multilayer laminate [14]

The determination of the relevant fiber direction can be calculated as a product of the principal stresses and the associated force flow. Using finite element calculation, the element-related stress tensor is converted by rotation of the coordinate system in a shear-stress-free form (see fig. 11) [13].

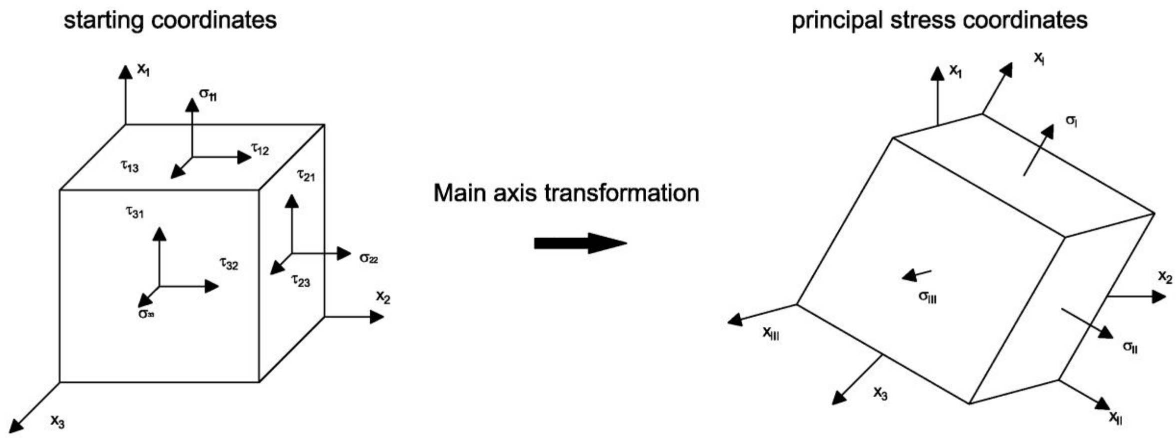


Figure 11: Principal stress transformation of the stress tensor, adapted illustration by [13]

By concentrating the fiber arrangement to match the load, one can make more effective use of a material's properties and minimize the material usage. In addition to using conventional fibers, the use of smart fibers makes it possible to actively respond to vibration and deformation behavior. The material should be selected in accordance with the specific requirements of the construction task (see fig. 3). Figure 12 shows an overview of the processing flow of parametric geometry generation and calculation as well as a comparative analysis of passive and adaptive structures. The adaptive structure shows a more homogenous strain image and has a more balanced material utilization.

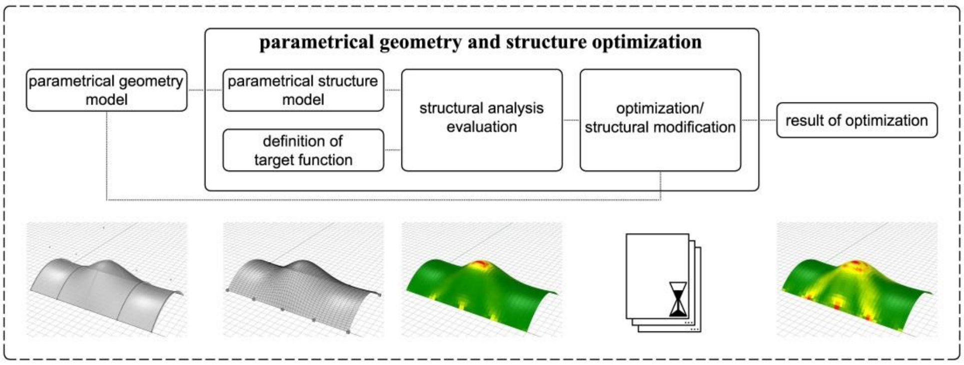


Figure 12: The use of parametric tools for geometry definition and analysis

4 CONCLUSIONS

The use of fiber-reinforced shell structures makes it possible to realize slender structures with large spans. In particular, the integration of adaptive fibers improves the resistance of a shell structure to critical deformation as well as its susceptibility to vibration. The parametric link between the geometry and analysis model discussed in this paper simplifies the process of structural analysis. The interfaces presented in this paper make use of existing CAD and calculation program systems and can potentially be integrated into similar program systems. The efficiency of shell structures can be further improved through the implementation of different optimization algorithms. The approach discussed in this paper makes it possible to draw reliable conclusions about a construction in the early stages of the design process and responds to current developments in planning practice.

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