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Structural optimization as a constitutive design tool in architecture

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Abstract

The melting of arts and sciences, of the liberty of design and the discipline of technologies in architecture is one major subject in architecture teachings when it comes to the role of the structure in architecture. Whilst more and more sophisticated analysis tools are developed, the connection between design and analysis is often missing, and the tools hardly find their way into architectural teaching. This paper describes the application of a commercial software commonly used for the optimization of components in the car and aircraft industries into the design courses of the Biberach University of Applied Sciences.

Keywords: structural optimization, design tools, generation and evaluation, complex geometries, CAD/CAM, design projects

1. Introduction

The minimization of a structure's self-weight plays a major role in aircraft and automobile engineering, where the dead load of a structure is to be minimised. In architectural design, the dead load of a structure is still often disregarded; however, the awareness of the amount of resources utilized in a building will have to be a growing focus in architecture (Sobek [1]). The possibilities of the applications of structural optimization are continuously advancening in the same amount as the more and more profound computational analysis tools in structural engineering. The connection between analysis and design is, however, not cultivated in the same amount of attention, even though the fundamentals are given (Ramm [2]). The commercial software OptiStruct provides an analysis and design tool as a specialization of the Finite Element Method. It was established in the architecture course at the University of Applied Sciences in Biberach and utilized for the generation of optimized structures in many different ways. The optimization algorithms are classified into topology, shape and sizing optimization in the common way (Bendsoe [3]., Schumacher [4]). An additional tool is the topography optimization application, being a special type of shape optimization tool where a structure with given topology is modified through beads, inducing areas of enlarged bending stiffness. It can be used for the design of folded structures.

When working with an optimization application of a Finite Element program for the generation and design of optimized structures, two aspects are essential:

1. Once an optimization has converged, there is no guarantee for a global minimum being found. Studies therefore need to be carried out varying geometries, side conditions and initial values of iterations, making sure the optimization algorithm has not converged to a local minimum.
2. The variation of geometries and side constraints is one major potential in the application of optimization algorithms for the design of structures. Rather than generating and evaluating geometries subsequently, it is the interactive design process, generatig and evaluating structures simultaneously, that bears the most productive possibilities for the design of structures.

The following simple example of an application of the topography optimization algorithm shows the process of coincidential optimization, variation and evaluation. An analysis model with given topology and varying support conditions is subject to a topography optimization. The objective function is the minimization of the compliance; the constraints are given by the bead geometry (minimum width, draw angle, height). Fig. 1-2 shows the two analysis models with 4 and 3 supports respectively; Fig. 3-6 show the optimization result
- without geometrical side constraints
- with geometrical constraints given through symmetry planes.

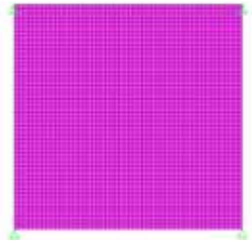
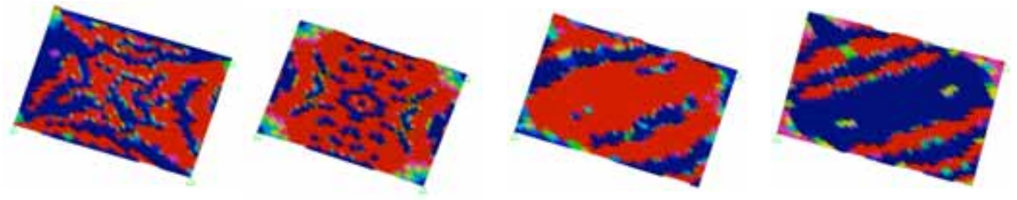


Fig. 1: Analysis model 1
Supports in 4 corners

Fig. 2: Analysis model 2
Supports in 3 corners



Optimization results / design proposals for the analysis models without / with symmetrical optimization constraints:

Fig. 3: Model 1

Fig. 4: Model 1 with symmetry conditions

Fig. 5: Model 2

Fig. 6: Model 2 with symmetry conditions

The geometries found through the optimization algorithm can be evaluated using a comparative diagram with the minimum of compliances achieved. The design proposals in Fig 3 - Fig. 6 are represented by the graphs of the optimization model 1 - model 4 in Fig. 7 respectively.

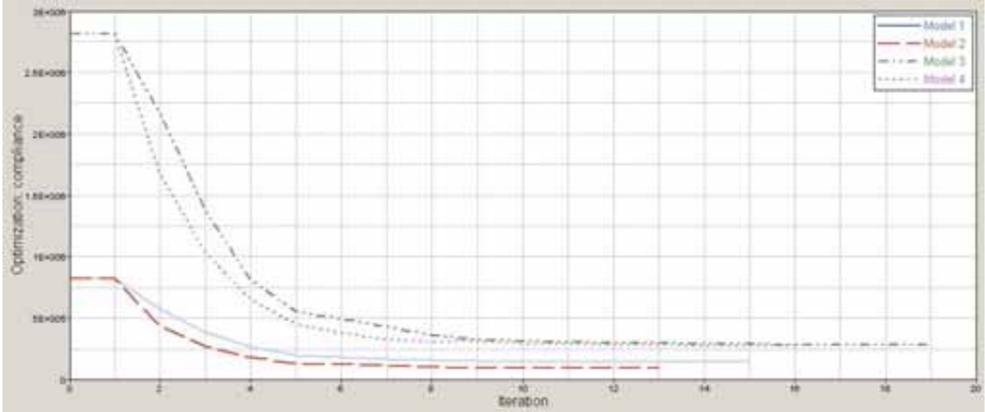


Fig. 7: Comparative graph of the optimization function

The comparative graph shows

- the starting value of the compliance, being larger for analysis model 2 which is feasible as model 2 has less constraints with the same structural topology

- convergence of the two different analysis models at different levels. At the same time, a different level of compliance is obtained for each analysis model when comparing the two optimization models without / with geometrical side constraints. It is obvious that a symmetrical analysis model should produce symmetrical design proposals; however, in some cases the difference might be neglectable.

It is shown hereby that the addition of geometrical costraints can help generate a comparative design proposal making sure the geometries obtained are close to a global minimum, for example when symmetrical geometries are not desired.

The examples shown in the following chapter deal with the application of optimization algorithms for the architectural design of structures.

2. Generation of folded structures for temporary roofs

The topography optimization algorithm of the OptiStruct package was used for a student project at the Biberach University of Applied Sciences. The design project was a temporary roof constructed as a folded structure of lightweight cardboard panels. The roof dimensions are approximately 6 m by 3 m, with the site opening up mainly to access the short sides, one of them widening up through the adjacent University buildings. The course was set up in the manner of an architectural competition (Lochner *et al*. [5]), with one of the projects to be realised in a scale 1:1 model.

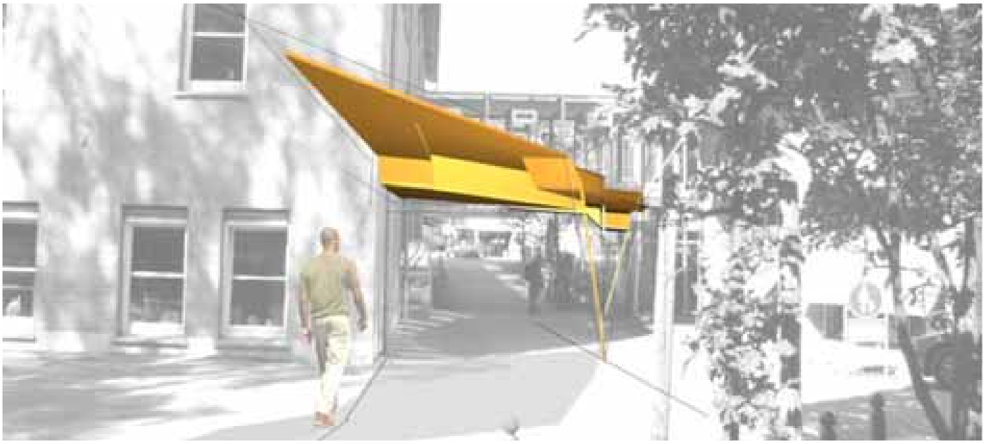


Fig. 8: Situation of the design project with example of design proposition

Given the site with a corridor situation opening up to a street crossing, the situation of the environment for the design project suggests non-symmetrical geometries. These, however, bear the risk of ot finding optimum structures with the optimization algorithm. Various studies therefore needed to be carried out with varying structural and geometrical conditions.

An example for the topology of the analysis and optimization model, the design proposal and its interpretation is given in Fig. 9 - 11.

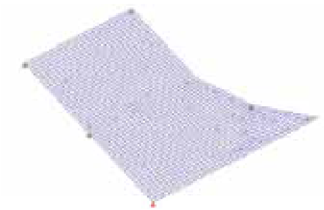


Fig. 9: Analysis model

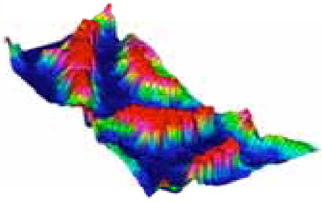


Fig. 10: Design proposal

Fig. 11: Interpretation

Fig. 12 shows examples for the different design contributions that were found through the variation of design topologies, support conditions and geometrical constraints.

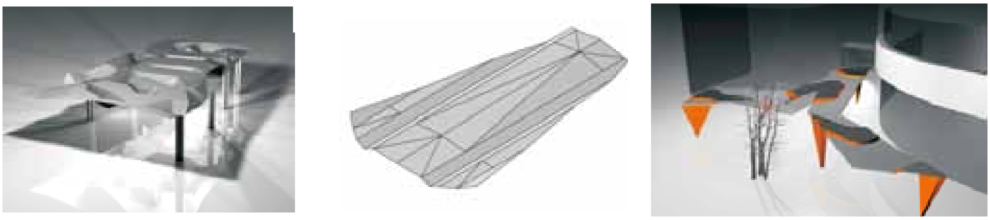


Fig. 12: Examples for different design contributions

The interpretation of the design proposal and its transfer into CAD/CAM software allows to provide the manufacturing drawings for the realisation of the project. The benefits of structural optimization as a design tool are therefore shown: both the "artistic" and the "technical" aspects of the design process are supported.

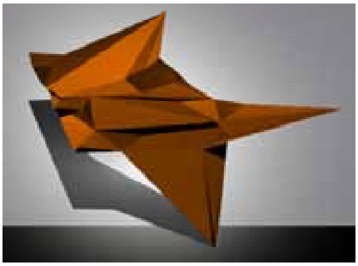


Fig. 13: Visualisation

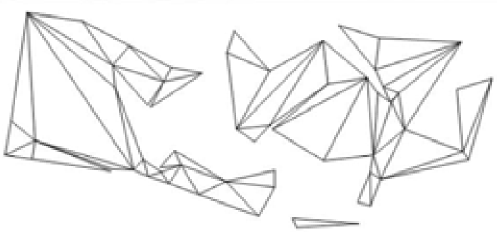


Fig. 14: Manufacturing drawing

In order to facilitate the realisation of the roof shown in Fig. 13-14, material tests were carried out in the laboratories of the company Zwick in Neu-Ulm, specifying the bending stiffness of the lightweight cardbord material which had been provided by sponsors.

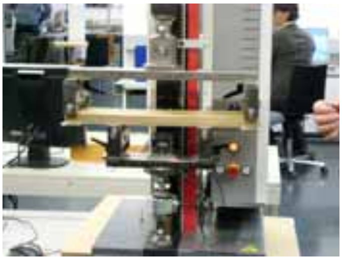


Fig. 15 Testing arrangement

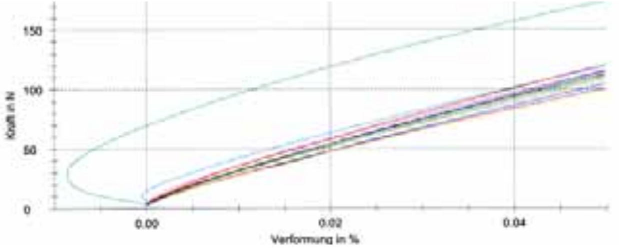


Fig. 16 Test results

The realisation of the chosen student project is still to be finalized. Independently of the construction progress, the conceptual process itself, using structural characteristics in a parametric design scheme, has shown to be a valuable contribution in the various methods of architectural design.

3. Development of a modular lightweight structure

The design of modules has become somewhat old-fashioned. However, it bears, for example, various possibilities in fields such as the application of curved lightweight concrete shells for prefabricated and/or repetitive structures. The project described in this chapter deals with the developmet of the geometry for the structure of an administrative building. The side conditions for the structural optimization were derived from the functions of the administrative building. The geometry of the structure was developed using topology and topography optimization tools. The project was developed as part of a master thesis at the Biberach University of Applied Sciences. The outline subject of this master thesis was the interaction of structure and shape; the design project described here had the purpose of developting an architectural project with a strong interaction of these features.

Fig. 17: Administrative building developed using optimization algorithms

Fig. 17 shows the result of the design project, being the practical part of a master thesis carried out in a theoretical and practical stage: a modular structure consisting of the repetition of additive concrete shells. The geometry of a single module was developed in two steps:

1. Topology optimization for the development of the global shell layout (Fig. 18).
2. Topography for the local optimization of the shell geometry (Fig. 19).

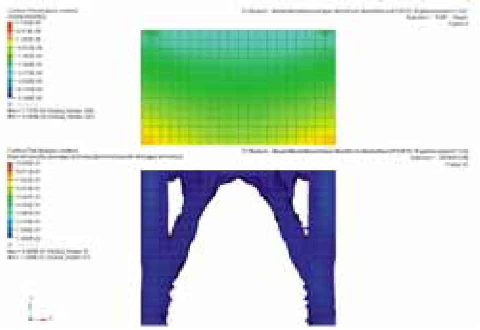


Fig. 18: Design proposal:
Topology optimization

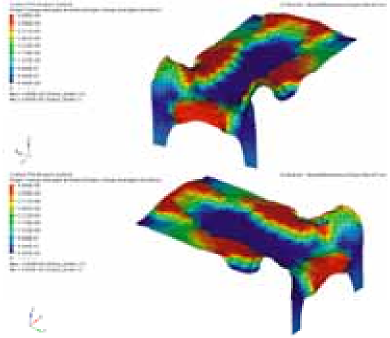


Fig. 19: Design proposal:
Topography optimization

The optimization of concrete structures for building structures is a subject nowadays often still neglected, as material costs and availability generally are not the most relevant design parameters. It is becoming more and more obvious though that resource friendly design and construction will play a major role in the architecture of the centuries to come.

The use of optimization algorithms provides possibilities for the generation of geometries as well as the simultaneous evaluation of structural feasability as well as aesthetic quality (Fig. 20-21). It should therefore be a major feature in teachings of architectural design.

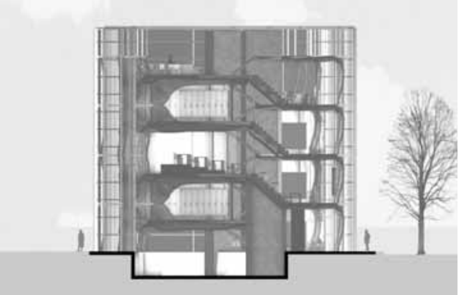


Fig. 20: Section drawing of the building

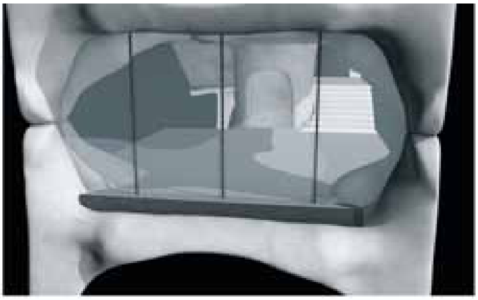


Fig. 21: Visualisation of the rough geometry

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