Geometry Studies using parametric Structural Models and Optimization Methods

Irmgard LOCHNER ALDINGER
Professor, Biberach University of Applied Sciences; Associate, Peter und Lochner; Germany
i.lochner@pul.ingenieure.de

Civil engineering and doctorate degree from the University of Stuttgart. Work experiences include Polónyi & Partners, Arup and the ILEK institute. Main research interest lies in the applications of aircraft and automotive design methods to structural and architectural design.

Summary

The generation of complex shapes and the parametric design of geometries play a major role in contemporary architecture. Many aspects, such as manufacturing methods (e. g. developable surfaces) or environmental aspects (e. g. shading), can be taken into account in the design process. The evaluation of the interaction between geometry on the one hand and structural performance on the other hand is often placed in the background, even though the fundamentals for their simultaneous evaluation are given. This paper describes applications of methods of structural optimization into the understanding, teaching and development of structural geometries. The studies carried out and presented here lead into the postulation of the systematic parametric generation of geometries using the methods of structural optimization, advancing the visualisation and hence the understanding of structural behaiour of spatial structures for practice and teachings.

Keywords: *topology optimization; simultaneous design and evaluation; parametric design; complex geometries; structural patterning; understanding and teaching of structures; design development.*

1. Introduction

The methods of structural optimization in conjunction with Finite Element Methods are used as a powerful design tool in the car and aircraft industry. This is due to two major reasons:

- the minimization of the dead load is an economical criterion for the design of mobile structures, aiming for the maximum possible input of payload, which makes efficient structures essential in order to be competitive in the market.

- the structural components developed in the car and aircraft industry are often of complex geometries, of manifold loadings and of versatile demands, which necessitates computation and post-processing tools.

In the building sector, these optimization methods are not yet an everyday tool in practice, although wide areas of structural optimization have been pioneered by scientists from the structural engineering sector [1]. Applications of structural optimization are a very useful tool for the systematic analysis of structural geometries since they produce on the one hand a quantitative comparison of design proposals and on the other hand a visually descriptive simulation of structural performance.

This paper takes off with a brief description of methods and procedures of design - in general, and in structural engineering. The following documentation of an analysis of Pier Luigi Nervi's ceiling structure for the Gatti wool factory leads to the question of evaluation and generation of structural geometries. The application of systematic parametric patterns for structural geometries, carried out with reference to a shell structure conceived by the architect Matteo Thun, shows the benefits of studying structures with parametric structural boundary conditions. As a conclusion, the benefits of a systematic application of the methods of structural optimization are demonstrated.

2. Design of structures

2.1 Design development and assessment

Like all designers, engineers take off with their design development by the analysis and assessment of the tasks and boundary conditions given by the design project. Starting analysis and assessment will lead us into different aspects of analysis, to different approaches to the problem solution and probably to diverging priorities being set (Fig. 1). First steps in the design process and evaluations of design parameters lead into loops to be taken, resulting probably in back and forth steps (Fig. 2) within the design process. Alan Holgate has developed two graphical illustrations of designers' paths to their individual design result. A branching and hierarchical geometry referring to "a sponsor's problem" shows the starting point, the solution of the task taking certain turns and ending in a certain problem solution (Fig. 3). The labyrinth on the other hand takes different starting points into account (Fig. 4).

Fig. 1: Display of information in a "tree" (Bader)

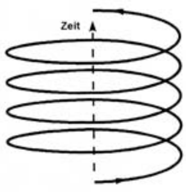

Fig. 2: Spiral looops in decision making (FOGIB)

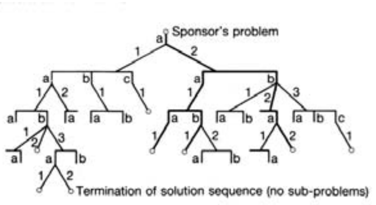

Fig. 3: "Tree" figure visualising designers' paths (Holgate)

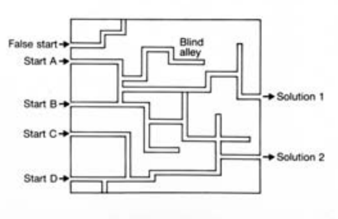

Fig. 4: "Labyrinth" visualising designers' paths (Holgate)

All of the illustrations show the designers' freedom to the ability of following a chosen track. This design track is limited, or guided, by constraints, design drivers and design goals.

2.2 Design drivers for structural geometries and lightweight structures

Manifold design drivers influence the design of structural geometries [2]. As in all design disciplines, a design driver can on the one hand be a limitation in freedom, on the other hand it is a useful tool for orientation within the arbitrariness of designs. The principles of lightweight structures can be used as a design attitude that might radically influence design outputs.

2.3 Generation and evaluation of structures

"Designing is: thinking in alternatives", as it was postulated by Curt Sigel. Engineers, architects, industrial designers, cartoonists start their projects with initial sketches, the design going from coarse to fine, developing refinement in scale and in shape. Connected with these steps is the evaluation and assessment of the produced object. The aspects of evaluation can be qualitative or quantitative attributes, often of diverging characteristics.

Aiming to cut back back the criteria into characreristics of structural behaviour, the assessment factors to be taken into account include the efficiency of the structure, i. e. the compliance (or stiffness) of a structure, the homogeneity of stress distributions (probably aiming for a "fully stressed design"), or the extent of material to be applied in a structure with the side constraint of a certain design goal.

3. Generation and evaluation of structural geometries - simultaneously

3.1 Object of study: the Gatti wool factory ceiling, designed by Pier Luigi Nervi

The ceiling structure of the Gatti wool factory, conceived by the Italian engineer Pier Luigi Nervi, is widely considered to be an icon of engineering and architecture, melting structural efficiency with high aesthetical quality. The structure with downstand ribs following the trajectory pattern of the point supported slab is recognizable in the works of Nervi [3], who was often developing structures finely conceived in three dimensions, allowing for light appearances through the play of light in spatial geometries.

Fig. 5: The Gatti wool factory ceiling structure

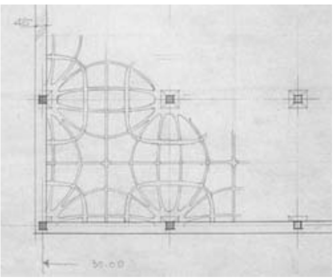

Fig. 6: Original sketch of the structure, CSAC, Parma (Italy)

The Gatti ceiling structure was chosen as an object of study in terms of structural performance because of its broad reputation of aesthetics and efficiency. Taking a closer look, the mapping of a downstand rib geometry derived from the principal moment trajectories of a slab into a spatially loadbearing slab structure is not merely traceable. The structural performance of a massive slab does not coincide with the one of an additive hierarchical structure, which is distinctive for the Gatti ceiling structure. Therefore, possibiliities of assessment of the structure according to Nervi have been examined.

The search of possible design drivers for the emergence of the trajectory rib geometry lead to branching structures in botanical geometries, to gothic cathedrals, to the fabrication methods established in the 1950s years, and to the geometries as found in bone structures.

3.2 Parametric geometry study

For the geometrical investigation of the structural performance of the trajectory rib ceiling, a parametric model was programmed [4] in order to produce and evaluate rib geometries with varying shape of the downstand beams (Fig. 7). The rib height and width were maintained, so that the material input would be the same for all geometries and therefore the structures would be comparable. Fig. 8 shows the geometries produced, with the original geometry being displayed in the middle and modifications shown on the left and right.

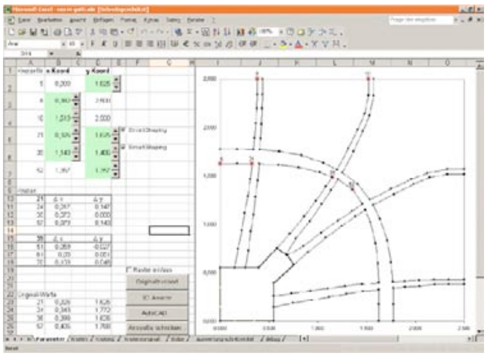

Fig. 7: Parametric programming of the rib geometry

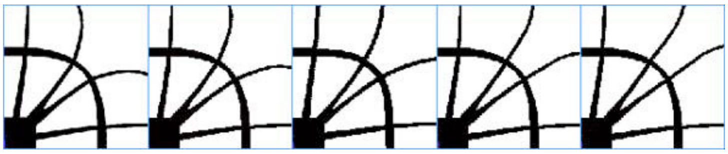

Fig. 8: Geometries produced by the parametric model, with FEM files being produced for structural analysis

The geometries produced were analysed and assessed with the main focus on their performance with respect to the compliance value and to the homogeneity of stress distributions.

Both studies showed that a quantitative assessment of the structure is not possible. On the contrary, it was shown that from the point of view of structural behaviour, the geometry of the downstand ribs is more or less deliberate: changes in geometry produce only local and qualitative impacts.

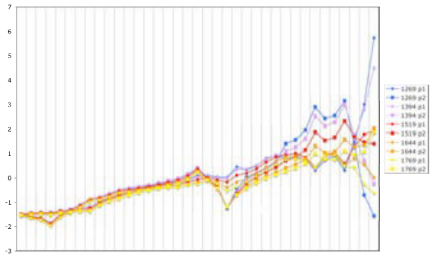

Fig. 9: Normal stresses at rib bottoms of the parametric models

As a conclusion of the various studies carried out in order to evaluate and assess the geometry and the structural behaviour of the Gatti ceiling, it was shown that

- the transfer of the load bearing behaviour of one structure into the geometry of another, at least similar, structure does not necessarily produce results of remarkable structural efficiency.

- there is a range of randomness in the generation of structural geometries where methods of quantitative assessment of structural behaviour do not identify distinct results.

The methods of structural optimization were therefore applied with the aim of producing a reference design, resulting from the aim of lightweight construction only. It was shown in this study that the purely "objective" design goal leads to other results than the geometries produced by Pier Luigi Nervi and his associate engineers. It can therefore not be proven that his structures follow an objective design law, while they are obviously guided and acknowledged by subjective valuations, which are very hard to take into account in any evaluation process.

4. Parametric patterns: systematic generation of geometries

Parametric design is nowadays very fashionable in architectural and structural design. New design tools allow to generate variations of a design, allowing to adapt geometries to local boundary conditions - be it structural demands, lighting conditions or formal conceptions

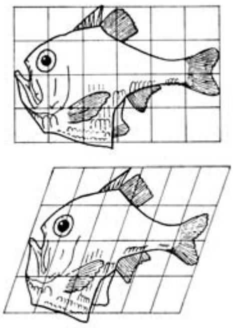

Fig. 10:Geometry study

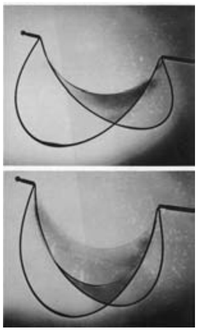

Fig. 11: Soap film study

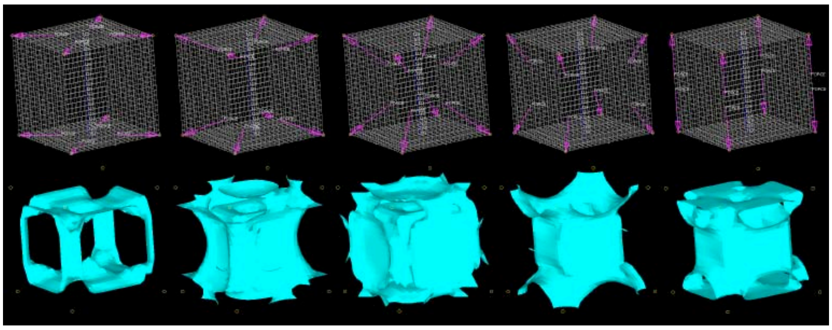

Fig. 12: Parametric topology optimization

Looking at examples of parametric studies, manifold examples can be found:

- parametrical geometries (Fig. 10): studies by D'Arcy Werntworth Thompsons dealing with the subject "On growth and form" [5];

- form finding studies with systematic variation of boundary conditions (Fig. 11): soap film studies (establishing minimal surfaces) within a margin defined by a curved wire carried out by Frei Otto and his team [6];

Fig. 12 shows the results of a parametrical topology optimization. The design space, the support condition and the objective function (minimize compliance with a given volume fraction of the design space to be employed) are maintained in all cases; the loading conditions are systematically varied. The isosurface plots of a selected density value of the design proposals show a logical connectivity between loading and optimization result. Just like the systematic variation of geometries or of boundary conditions, systematic studies using the methods of structural optimization can produce logical varieties of structural systems, contributing to the understanding and design development of structural geometries.

4.1 Object of study: a series of shells for an "Eco Hotel", designed by Matteo Thun

The design for an "Eco Hotel" in South Tyrol, the concept being developed by the architect Matteo Thun, envisages a series of shells cautiously embedded into the landscape. The holistic approach of the trade mark "KlimaHotel" targets to ensure sustainability for the tourism of the future by establishing an international standard for hotels with an ecological and environmental purpose. In the given design project, the expansion of an existing hotel is outlined, focusing on minimal impact on nature and minimal limitation of the impressive mountain prospect. The concept is determined by appartments carved into the mountains, the visible part being roofed by smooth shells moulding the hills, and the only visible part remaining the fully glazed facade of the appartments.

Fig. 13: Architectural sketch and visualisation of the Eco Hotel by Matteo Thun

As a possible continuation of the design scheme, a series of very elementary shape studies for spatial structures was carried out, using the methods of topological optimization with parametric structural boundary conditions.

4.2 Parametric patterning

4.2.1 Procedure

For the development of the shape study, optimization models were developed with different volume proportions were created. For a selected volume geometry, the loading cases "self weight" and "distributed loading on top surface" were modeled. For both loading cases, two optimization objectives were formulated:
- minimize compliance, with a given volume fraction of material to be applied;
- minimize volume of the structure, with a deformation constraint as a side condition.

For both loading conditions and optimization formulations, topology optimization was carried out and interpreted as shown in Fig. 14 and Fig. 15.

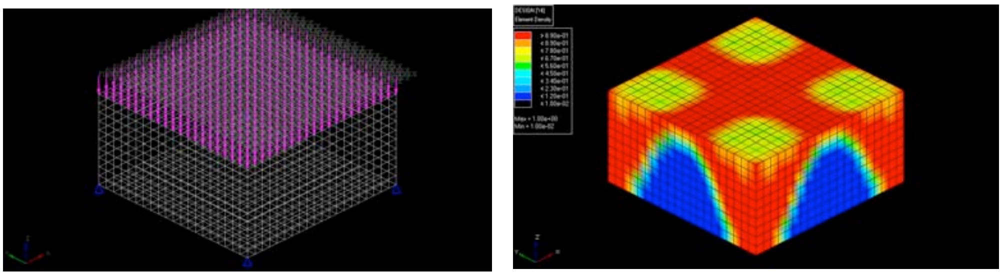

Fig. 14: Volume and finite element meshing of the design space for topology optimization; contour plot of design proposal

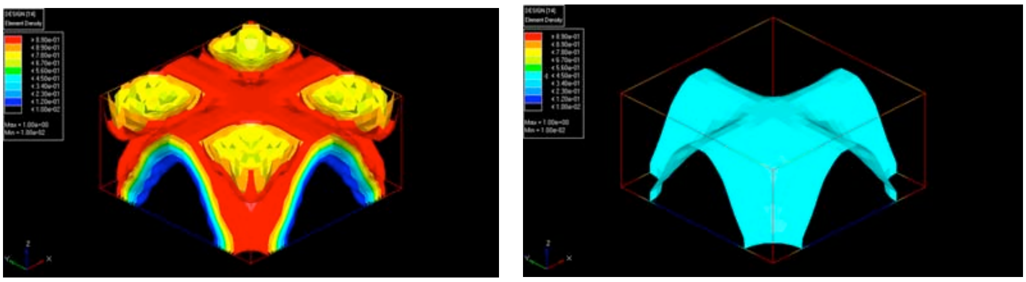

Fig. 15: Isosurface plot of design proposal, legend based, and display of a selected density level of the design proposal

The result of a topology optimization under distributed loading on the top surface with the objective function of minimal compliance under the side condition of 40% of the design space to be filled with material is shown here. The structure is supported in the four corners. As a result, the concentration of material in a geometry resembling a cross vault is produced. The design proposal shows intermediate values of material densities in between the actual structure and the loading applied. These intermediate densities can be avoided when applying gravity loading instead of distributed loading. Switching off the intermediate densities clearly shows the characteristic shape of the geometry that was produced by the optimization algorithm.

4.2.2 Systematic generation of geometries

With this optimization model generated, a systematic variation of the supporting conditions was carried out, with the loading and the optimization objective and constraints remaining unchanged.

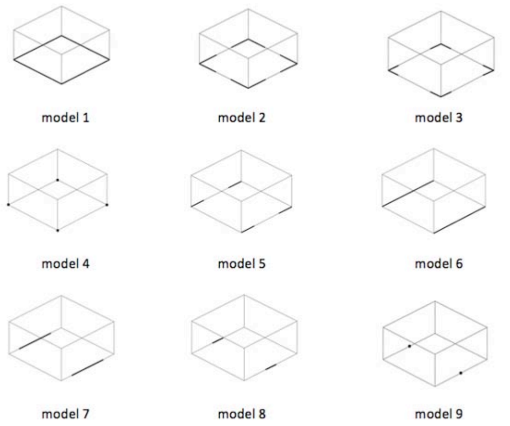

Fig. 15: Variations of support conditions

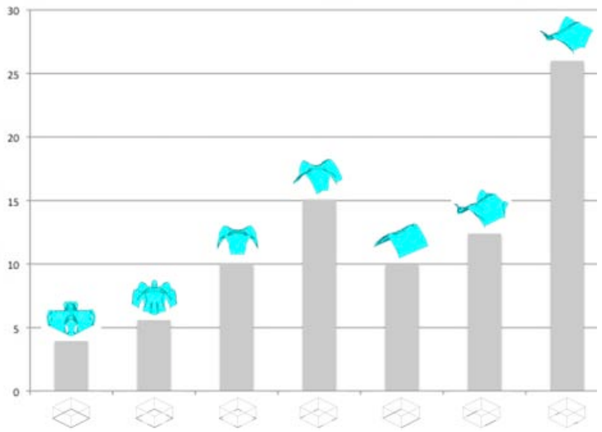

Fig 16: Comparison of optimization results

The optimization study creates comparable structural geometries, since in all cases the same material input was applied. The value of compliance of the design proposals created can be directly compared (Fig. 16). The parametric patterning of structural geometries produces qualitative and quantitative results and a useful design tool for the generation of spatial structures.

5. Conclusion and Outlook

The application of methods of structural optimization in the design of structures is a very powerful desing tool. Further studies include variations in the design of bridge structures (Fig. 17)

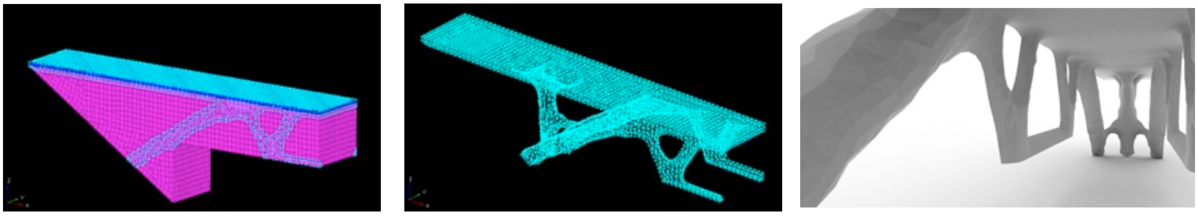

Fig. 17: Bridge design study, optimization result and rendering

The bridge study was produced by students of architecture (Dominyka Mineikyte) and engineering (Yao Yao, Yuki Otsubo) from the Princeton University during a workshop held by the author at the Structural Form Finding Lab (Prof. Adriaenssens), the rendering was produced by a student of architecture (Andreas Reus) from the Biberach University of Applied Sciences.

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