A Topology Optimization Approach to Learning in Architectural Design

Michael Mullins¹, Poul Henning Kirkegaard¹, Rasmus Zederkof Jessen² & Jens Klitgaard²
¹Department of Civil Engineering, Aalborg University, Denmark
²Department of Architecture and Design Aalborg University, Denmark

Abstract. Topology optimization methods offer an interesting tool for architects and engineers as a rational basis for the choice of a structure’s initial form, particularly as developments in computer software are compatible with this approach. This can be argued from ecology, resource savings, static load design, financial and a number of other pragmatic reasons. But in an artistic/architectural perspective these are not decisive. Analogical design qualities include a tectonic appreciation of the properties of materials, metaphoric interpretation of intention and considerations of context. The paper describes an attempt to unify analytic and analogical approaches in an architectural education setting, using topology optimization software. It uses as examples recent student projects where the architectural design process based on a topology optimization approach has been investigated. The paper describes and presents results obtained by the students during the project. Further, a discussion is delivered concerning the improved understanding of tectonic design obtained by the student during the projects.

Keywords. Architectural education, Topology optimization, Tectonic design.

Introduction

Contemporary architecture is often a complex interplay between aesthetics, technology and construction. The successful outcome of such projects requires design input from architects and engineers at an early stage of a design process in which computers play an important role. Architects and engineers both employ iterative multi-stage design procedures, starting with initial conceptual design and progressing to more detailed final design. There are however essential differences in approach of these disciplines.

Conceptual design for an architect can be abstract affair, with content that might be more amenable to poetic interpretation than by geometric representation; as an example we may take the ship, bottle rack, and hut used by Le Corbusier as sources for the Unite d ‘Habitation. On the other hand, conceptual design for a structural engineer tends to be more pragmatic in nature, i.e. the choice between an arch and a suspension structure, between concrete and steel. The difference in approach is typified by the problem of
expressing psycho-physiological spatial concerns in the mathematical space of computers. If compromises unacceptable to either of the parties are to be avoided, successful integration of the two approaches must necessarily enter earlier in the design process.

Yet these differences tend to vanish in some of the most successful examples of integrated architectural and engineering design, exemplified by Santiago Calatrava, Antonio Gaudi, Pier Luigi Nervi, Felix Candela and Buckminster Fuller (Tzonis, 2002). Their buildings affect one through certain expressive qualities which clearly have something to do with the play of forces and corresponding arrangement of parts in the design. These architectural qualities, which are expressive of a relation of form to force, provide a definition of ‘tectonic’ design (Frampton et al., 1995).

A growing potential for the computer to support tectonic design is argued by Neil Leach, where computer technologies “are now being used to offer insights even into the realm of the tectonic. In particular, they are allowing us to model – with increasing sophistication – the material properties of architectural components” (Leach et al., 2004). These properties may be said to be increasingly necessary in computers applications for architects and students: “I found teaching in many architectural schools that the computer is a very seductive animal, and that fantasy is very quick to be modelled on the screen. But, more and more, as I was teaching across the world in different places, I saw that as with the dead end that hi-tech got into, the final modernist statement of the glass and steel box, ... that actually we are in danger of computer-generated architecture going that way too if there was not some kind of twinning with the structure in a fundamental way” (Ito and Balmond, 2002).

In seeking for a close relation between form and structure in architectural design, structural optimization software appear to offer solutions; the optimization method offers an interesting tool for architects and engineers as a rational basis for the choice of a structure’s initial form. This can be argued from ecology, resource savings, static load design, financial and a number of other pragmatic reasons. But in an artistic/architectural perspective these are not decisive. Analogical design qualities of form might include an expression of the properties of materials, metaphoric interpretation of intention and aesthetic considerations of context.

**Shape and Topology Optimization Tools**

An optimal form can be obtained using topology and shape optimization tools developed during the last decades in combination with the finite element method (Bendsøe and Sigmund, 2003). Such optimization techniques imply that structures, given a predetermined load scenario, can be obtained with the minimum of weight. Traditionally

Figure 1: Shape optimization of a wall panel (Frier et al., 2004).

Figure 2: Topology optimization of a wall panel (Frier et al., 2004).
shape optimization techniques have been regarded from a black box point of view; providing an optimized structure based on an initial design defined by the user. In shape optimization, a shape is defined by means of orientated boundary curves or boundary surfaces of the structural body, and the optimal shape of these boundaries is obtained. The boundary of the design must be described in some parameterized form, e.g. using straight line segment, spline control points or circular arcs. In this way, the design can be described by a limited number of design variables, e.g. the spline control points. In order to illustrate the concept of shape optimization an example with a wall panel which contains a window and a door is considered, see figure 1.

Only two design variables are considered to completely describe the design, x1, being the height of the half ellipse defining the top of both the window and the door, and the other, x2, being the width of the window. In this way, a rather complicated geometry can be described by means of a few design variables but on the other hand the finite element grid turns out to be more complicated than would be the case in a topology optimization problem. The shape optimization problem can be formulated in several ways. In statics, it is customary to minimize the weight or volume of the structure with respect to constraints on stresses in the structure. Even though the number of design variables may be moderate, some other considerations may still complicate things.

Various topology optimization method have been developed, such as the ODESSY software system since 1991 at the Institute of Mechanical Engineering (IME), Aalborg University, for modelling, parameterisation, analysis, sensitivity analysis, and optimization of engineering designs (see http://www.ime.auc.dk/research/design/odessy/Ods_index.htm). In terms of analysis, ODESSY is similar to many well-known computer-aided engineering systems such as Nastran, ANSYS, COSMOS/M and others.

A particular feature of ODESSY is its ability to reach beyond mere analysis into the synthesis of engineering designs. The method generates the optimal form of a structure within a ‘design space’ - the universe of possible designs that will fulfil a given need - defined by the designer, who also provides positions for structural supports, loads and types of materials. ODESSY uses optimization techniques or, more specifically, mathematical programming, to find the best combination of parameters. Without further input, the method will generate a structural shape within these parameters, thus providing the designer with a conceptual idea of an efficient geometry (Frier and Kirkegaard, 2005, Frier et al., 2004).

The design process is started in a reductive process, i.e. material is removed from an initial general design domain. The finite element method (FEM) is used to obtain the structural response of the structure, thereafter the structural compliance is minimized; i.e. structural stiffness is maximized, with a constraint on the volume of the structure. Design variables are formulated by introducing relative element densities, ranging from zero (no material) to one (solid). Topology optimization of the wall panel in figure 1 is shown in figure 2. Topology optimization is a much more flexible design tool than classical structural shape optimization, where only a selected part of the boundary is varied without any chance to generate a lightness hole, for example.

Case study I - A Roof Construction

This student study (Jessen, 2004) deals with topology optimization used to determine optimal material usage. It was the study’s objective to enquire whether this work method can be used to integrate construction/engineering considerations during the architectural design process. The study proposed a new roof enclosure, spanning 9m over two railway lines and parts of the platforms at a train station. The built context determined a maximum height of 8m and a conceptual aesthetic in
Figure 3: Simple definition of design space for a pedestrian bridge.

Figure 4: Expression of forces after topology optimization.

Figure 5: Redefinition of design space.

Figure 6: Result of topology optimization after redefining design space.
keeping with its siting. A minimum number of supports were sought, to allow unhindered circulation to passengers and trains.

In the study’s initial ODESSY enquiry, the design domain was defined in as simple a manner as possible, using only overall dimensions of the required structure. The result did not satisfy the study’s formal considerations. Consequently, both the design domain and position of supports were altered to meet these demands, each result varying considerably in form from the previous attempt.

Subsequent to the formal requirements being met, material usage was varied, giving further differences in results. A solution judged suitable to the initial conceptual focus is then extracted for further working in 3D modelling software.

Case study II - A Pedestrian Bridge

The basis for the student’s study (Klitgaard, 2004) is a 66.5 m long pedestrian bridge, spanning the Limfjord harbour. The metaphor of a hand supporting a spanning structure was the guiding concept.

In this study’s first attempt, no intermediate supports are used. The bridge’s end points are fixed in foundations. Loads are applied at specified points. In the first attempt, these are as shown in figure 9. In practice, the loads at the endpoints are considered as support by the programme. The loads on the bridge itself have decided effects on the optimised geometry, being primarily transferred diagonally to the support points and secondly, horizontally across the bridge midpoint. The result is clumsy,
appearing heavy and unnatural, and it is concluded that a 40 meter span is not optimally solved by a horizontal, 1.5m high massive beam, as seen on figure 10.

In the second attempt, two fixed support points are introduced, approx. 15 meters from each end. In addition, loads are applied at intervals of 3.5m across the length of the bridge (figure 11).

The resulting optimization process gives a completely different form from the first attempt (figure 12). Functionally, the arch gives adequate potential for passing beneath, and the attempt is on the whole more interesting. It offers a further working of the arch; it bears a certain similarity to Calatrava’s lattice structure at Kansai airport and can form a departure point for architectural design.

In the third and final attempt, a support is added to the centre of the bridge (figure 13). The loads and material parameters are the same as in...
the previous attempt, thus the changes reduce the spans and effect the distribution of loads.

The results show the dominating arch being replaced by a fan-like structure (figure 14), based upon a sine curve. This approximates the initial concept of a supporting hand. A further working of the design could undoubtedly result in a unique and aesthetically pleasing structure.

**Conclusion**

In the case studies described above, conceptual work on formal and aesthetic considerations preceded the optimization process by ODESSEY. These considerations were used to continually assess the computational results, based on functional requirements of the briefs.

It was found that the tool was suitable for limited architectural use under these conditions. Design input was constrained by too few parameters. There is a need to develop greater user input and direction in the computational process; presently this process is wholly automatic, once the initial parameters have been set. The ability to base initial design space on metaphorical imagery, which provides the fundamental gestalt of the design solution, is one such possible improvement. In addition, the graphical user interface can be much improved, particularly in relation to other CAD and 3D modelling software commonly in architectural use. These improvements would go some way toward achieving a suitable sketching or initial design tool, capable of producing optimal construction solutions, while simultaneously realising the architect’s aesthetic requirements.

Tectonic architecture results from a design process where concept, form, structure, material and surface amalgamate. Topology optimization software has the potential to be incorporated into a design process of this kind, not only as an analytic tool to be applied to a complete design, but also as part of the initial design exploration.

**References**


Frier, C. and Kirkegaard, P. H.: 2005, Tectonic De-


