Structural Analysis as Driver in Surface-based Design Approaches

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This ongoing research argues for novel strategies to integrate structural analysis data in an architectural design approach. Instead of a linear procedure of synthesis, analysis and post-rationalisation a synthesis/analysis loop is installed that uses structural analysis data as design driver from early on. The approach is not aiming for a pure force-driven form-finding or optimization process but regards structural performance as one design criteria among others. Equilibrium between multiple parameters is aspired instead of a single-parameter-optimum. The research is conducted by a custom-made digital interface between a 3d modelling software and an application for structural analysis of space frames structures. Surfaces are translated into meshes with supports at user-defined nodes and then exposed to its dead load in the structural analysis software. The resulting nodal deviation is feed into an algorithm that steers the appropriate reaction towards the local stresses and deviations, taking into account the mesh topology, its supports and their position in the mesh. The initial mesh is optimized in shape transformed back into a double-layer surface model in the 3d software which evolves into an interconnected two-layer space frame. An instant feedback from synthesis to analysis and vice versa is installed. Analysing techniques migrate into the realm of synthesis.

Keywords: Optimization; collaborative design; structure and surface.

The protagonists of generation and analysis

To some extent the design work of architects and engineers is comparable. Both domains share common processes and strategies when they work in their specific realms. In an iterative process analysis, synthesis and evaluation is conducted until a satisfying solution is developed. Unlike optimization structural and architectural design problems are not always obvious nor are the paths that lead to their solution. In consequence the analytical and the generative part of the work are not separate, consecutive tasks but generally coalesce into one coherent event. An early
design proposal might reveal the need for additional analysis or shifts priorities which then restarts the next design cycle.

On the other hand the strategies of structural engineers are different from the ones of architects because their tasks are different. David Billington describes structural design as an art independent from architecture. Engineers design huge structures with mono-functional requirements. The shapes are defined by forces in the material. The goal is to reach maximal efficiency in material use and economy issues while creating an aesthetic structure (Billington, 1985).

Architectural tasks are usually defined by complex networks of requirements. All nodes in this network like program, circulation, light, material, structure, budget etc. are interrelated and interact with each other. Building components never serve only one purpose and practices like UN Studio seeking for inclusive strategies that map a multitude of functions to single elements (Van Berkel and Bos, 2006). A separated optimization of single aspects within such a cluster of requirements as proposed by John Page (Jones, 1970) is not appropriate because it ignores the intensive interactivity between the single aspects.

In a collaborative design process engineers and architects embody different roles. The architect synthesises a proposal based on the analysis of the multidimensional network of requirements which consecutively defines the “design problem” for the engineer. Structural issues are becoming an additional node in the interconnected network of different and sometimes contradicting architectural demands that needs to be analysed and evaluated. The scope of the engineer within the design team is shifted towards analysis. Engineering software is used as a means to predict the performance of a building and its structural system by simulation of material systems, construction and loads. But simulation is always based on a model and therefore not helpful for its synthesis. For example every form finding process starts with a normative system (the model) that is then exposed to external forces in a physical or digital realm. The system itself has to be defined in advance. Simulation can be seen as a technology while the analysis of the simulation result is a strategy or technique to refine the investigated design proposal.

As stated above a design process integrates synthesis and analysis and their permanent interaction and interrelation. This research aims for a further integration, the one of multiple disciplines within the design process. The results of structural evaluation are supposed to inform the generative work of the architect which then loops back to further analysis. The simulation technologies and analytical techniques migrate into the synthesis part to become a design driver.

**Surface-based design**

Surface-based design approaches have become widely used in architecture through Bspline-modelling software. The surface becomes a representative for a multitude of different aspects of a design beyond its initial function as a border between a volume and its environment. It is a two-dimensional object unfolded into the three-dimensional space without any material thickness. But instead of treating the surface as the border condition, it is often perceived as the object itself. This misconception of a surface digitally representing a physical building component is – at the latest - revealed when the surface is translated into build form with structural requirements, material thickness and material properties. To overcome this conceptional flaw and accomplish construction requirements the strategy of the design surface (Kilian, 2006) was recently introduced into the design practice. The two-dimensional surface is used as a guiding geometry to host three-dimensional building components. The overall morphology of the initial surface is represented by components that fulfil fabrication constraints. The concept of the design surface is used in this research to generate a mesh aligned to the guiding geometry.
The process starts with a surface that represents an initial architectural design idea. This surface is translated into a mesh with a specific topology. The mesh and user defined supports are the starting point for a form optimization in the structural analysis software. Deformation of the mesh under the influence of its dead load is seen as a means to reduce bending forces in the geometry. Cantilevering parts are treated in a different way. The optimised mesh is then transferred into a surface model in the 3D modelling software (figure 2).

**From surface to mesh**

The uv parameter space of the surface is used to proliferate meshes with specific topologies along the surface. Triangular, quadrangular or hexagonal meshes with different resolutions can be generated depending on the user’s choice. The mesh incorporates the overall shape of the initial B spline surface and acts as the normative model in the structural simulation.

Before transferring the mesh into the analysis software the supports have to be defined. Supports are located at the nodes of the mesh; their location can be defined in different ways. The user can choose the position and number of supports; they can be placed randomly, at the corners or at the lowest nodes of the mesh.

Mesh and support positions are transferred into the structural analysis software for space frame structures via a custom-made Visual Basic interface. The architectural language represented by the B spline surface is transcribed into a set of data suitable for structural simulation. Nevertheless in this stage of the process it is important to stress that the analysis
Form optimization

The mesh does not act as a proper structural system yet. But exposed to its dead load its nodal deviation shows similar behavior than a hanging chain model. Depending on the topology of the mesh, the bending resistance of its members and the support position, the initial mesh is deformed. Turning the deformation upside down leads to shell-like structures with reduced bending forces (Mangelsdorf, 2006). However the difference to pure form finding lies in different boundary conditions and support positions that also allow cantilevering structures. The start condition is defined by a Bspline surface incorporating a morphology that is driven by architectural criteria not necessarily related to structural issue. It is not a neutral plane that is transferred into a manifestation of the existing force flow but an articulated and differentiated shape that is exposed to another parameter in the design process: the structural performance.

The analyzed nodal deviation is feed into an algorithm that steers the appropriate reaction towards the local stresses and deviations, taking into account the mesh topology, its supports and their position in the mesh. The interpretation of nodal deviation is followed by two approaches to integrate these results in the architectural design process. Both approaches are currently investigated.

The single-surface form-optimization

Every node is analysed according to its relative position in the mesh and the supports. Cantilevering parts of the mesh are treated differently than nodes between supports. While mesh parts between supports can act in a shell-like manner bundling forces into increasing tension and compression the cantilevering areas have both types of forces within the same member. Reversing the nodal deviation would not be a suitable way to deal with cantilevers. A geometric optimisation in general is less effective in these areas. However cantilevering structures are consciously included in this research because it’s a common element in architectural design practise.
The deviation of cantilevering nodes is set in relation to the maximum deviation instead so that affected parts are lifted slightly (figure 4).

The refined geometry leads to a structure with increasing axial forces. Since the initial surface is not necessarily symmetric and the supports are located in inappropriate positions axial forces will always be accompanied by bending forces. The form is not “found” by the most efficient force flow instead the already articulated geometry is optimized.

The result is a mesh that is feed back in the 3D modelling software based on the optimised nodal positions. This approach was tested with a surface that went through the above described process (figure 5). The optimized mesh is transferred back into a B-spline surface. The new surface is supposed to incorporate an improved structural action concerning deformation because its overall form went through the optimization process. To prove this assumption the initial surface and the optimised surface are compared in a finite-element analysis software. The result shows a significant decrease in deformation in the cantilevering area which also leads to less bulging between the supports (figure 6).

The improved surfaces still incorporates the morphology of the initial surface which was driven by architectural design parameter. At the same time the shape is slightly deformed and adapted to inherent stresses and deviations. Structural analysis is becoming a driver for geometry (Saski, 2004). Different mesh topologies, mesh resolutions and support positions and their influence on the resulting geometry are tested in several iterations. The interactions of surface geometry and mesh topology can be analysed instantly through the provided interface between both software packages. An instant

Figure 4
Non-optimized (left) form, superimposed optimized form (right)

Figure 5
FEM analysis of non-optimized (left) and optimized (right) form
feedback from generation to analysis and vice versa is installed.

**Structural volume**

In the second approach an additional layer is added. The initial mesh evolves into an interconnected two-layer mesh that is transformed back into a double-surface model in the 3d software. The distance between both surfaces refers to the local deviation in the analysed mesh. The space between upper and lower surface is used as a volume for a structural system, i.e. a space frame structure.

The surfaces now act as the border representation of a volume and not as objects themselves. The conceptual flaw of surfaces with zero thickness is overcome by a space that can be used in different ways:

The solid approach: A construction volume as a “black box” where any kind of construction is hidden by the outer surfaces. Structural aspects are only reflected by the dimension of the volume. An approach that is suitable for concrete construction where structural performance of steal and concrete are not expressed in a differentiated structure.

The space frame approach (figure 5): A structural space frame generated by nodes and interconnecting poles. Structural components are differentiated according to local stresses and support positions. In an ongoing iterative process elements that are not exposed to loads can be removed.

**First conclusions**

The design process is driven by architectural and structural parameters simultaneously. The negotiation between different and even conflicting aspects yields solutions that are optimized during the generative process instead of being post-rationalized afterwards. The procedure is an approximation for the early design stage that offers architects the possibility to integrate structural aspects into their work and use them as design driver.

![Figure 6](Space frame model)
This research aims to integrate structural optimization strategies in the architectural design process to improve a design method. The presented interface between 3D modeling software and structural analysis is considered as a first step to integrate optimization into architectural design.

**Next steps**

The presented surface mesh interaction is a useful tool in the early design process. The global deformation and nodal deviation of the normative model are investigated and used to refine the overall shape of the surface and the definition of a construction volume between two surfaces. The mesh from nodes and elements is needed as an interfacing set of data that relates surfaces models to the data input need of the structural analysis software. The nodes and elements itself are of no interest in that phase.

In the next step the space frame will be further differentiated by analysing every single member of the system. Whereas the analysis software was used as a means of form finding in the first cycle it now delivers detailed information about section forces, bending forces and the moments of space frame elements. This information is used to differentiate overall space frame topology and profile dimensions referring to the specific required performance of individual elements. All elements of the space frame are analyzed individually and removed in case they don’t carry any load. This will lead to an optimized structure where every element can be differentiated. The differentiation is driven again by architectural and structural parameters.

Again architectural issues are defined by areas, volumes and sight lines that are supposed to be free from structural elements. The elements of the space frame structure are orchestrated as an interdependent network of elements. Zones of high stresses are densely populated while zones of low stress open space and views. In such a model “no clear distinction exists between ornament and structure, as neither occupies distinct zones” (Reiser, 2006).

**References**
