

## REFRAMING TEXTILES INTO ARCHITECTURAL SYSTEMS; CONSTRUCTION OF A MEMBRANE SHELL BY PATCHWORK

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**Summary.** In this paper different qualities of architectural textile techniques and tectonics are explored. By using a reframing strategy micro techniques and tectonics as used in fashion and textile design are evolved into an architectural scale. To reveal the quality of this reframing procedure a case scenario has been executed. By reframing patchwork techniques into a form-active shell geometry, a design is made. To reflect upon the case scenario a structural analysis by using Abaqus software has been performed.

### 1 AIMS AND MOTIVATIONS

With a broader knowledge on formfinding and membrane engineering, for the last decade form-active structures settled into the architectural vocabulary more and better. The structures proved to be, for instance, light weight, easy retractable, durable and recyclable. Most of these properties go well with nowadays conscious design culture. Because of a rich and notable form language of fluid lines and natural shapes, integrated climate control and media capabilities, the structures are often used in avant-garde architecture to positively brand certain events and companies. Given this development, these structures proved to be of big influence to concepts of forthcoming designers and architects.

Because of a rather unconventional design strategy, structural membranes don't adapt very well to normal given architectural situation. Sometimes the introduction of these techniques late into the architectural process proves to be more than a challenge. To provide textile design with a more diverse vocabulary, the researchers started working on a broader view of textile techniques in architecture. By a reframing strategy micro tectonics as used in fashion and textile craft are scaled to architectural dimension, specific textile qualities were innovated into an architectural variant. In some cases using the same techniques but changing its materials suffices. Other techniques demanded a different design approach.

## **2 REFRAMING TEXTILE SYSTEMS**

Since halfway nineteenth scientific research as a base for professional practice has excelled rapidly. Research with a positivist background supported practicing designer and engineers with applied mathematics and science-based technology to contribute to a society based on science. In the positivist approach, applied to this research, research and design was practiced as a rational process. With this design methodology being more influenced by theory of technical systems than by designers and design problems, positivism didn't apply well to all fields of research. In reaction to the positivist research, constructionist methods in research and design techniques were explored. These constructionist methods were based on reflection-in-action; learning by doing. With the general positivist problem solving design methodologies on one side, constructionist theories defined research problems as unique. In general, constructionist methods were opted by arts and the social sciences. [4] In particular the work of ILEK has been a well known example of reflection-in-action. [10]

Professional practice is a process of problem solving. In scientific research problem setting is a significant point and well described in recognized research methodologies. Designerly research on the other hand, generally cannot describe the research process as accurate as its scientific counterpart. With ill-structured, more emotional described tasks the design process has developed differently from the scientific approach. In research by design, ill-defined problems are framed instead of set. By framing the problem a solution space is defined. By converging the framed research description through reframing strategies to an editable research description, the solution-space is narrowed down simultaneously. [2]

Design and technology have always been in close contact. Both share a history of doing and making. Both involve knowledge from both sciences and the humanities to be more than just applied sciences. [2] In the balance of skills and science, doing and making is mostly ahead of understanding. [1] Like the early ILEK research, contemporary geometrical research requires physical feedback to progress in unknown territory. For contemporary digitally driven research, material reflection is as necessary as before for the research to remain constructionist instead of positivist.

### **2.1 Reframing Strategy**

In constructionist research, reframing is used to discover pleasant nooks, views and soft back areas to evoke a potential new coherence. [1] By reframing a problem from the existing frame into another it is partially released from former prejudice and conventions. Some new defined

frames may fit the contours of the former framework better than other. A bad fit for instance, can generate interesting reframing alternatives. A good fit on the other hand can generate interesting outlooks and research solutions.

With an interest in architectural structures and textile design, complementing frameworks were generated. For textile design a framework of textile techniques and textile tectonics is made. For structural design the framework of Structure Systems by Heino Engel [5] is used. By framing an instance from one framework into the other, textile-structure combinations originate. Bad fitted combination will be rated with a low success rate, well fitted combinations will be rated with a high success rate. A bad fit mostly originates from a misfit in textile geometry to the structural description. A successful fit is generated when the textile geometry complements the structural behavior. When a successful fit has been obtained, the potential of the reflective conversation continues. [1]

**2.2 Textile Framework; Textile Techniques and Tectonics**

To be able to frame and reframe textile-structure combinations efficiently, frame analysis is performed. By describing the content of independent frames, quality of combinations can be rated in advanced.

|                             |                                 |                                |                                 |
|-----------------------------|---------------------------------|--------------------------------|---------------------------------|
| Form-Active Systems<br>▼    | Surface-Active Systems<br>▼     | Section-Active Systems<br>▼    | Vector-Active Systems<br>▼      |
| Ruffling Techniques<br>▼    |                                 |                                |                                 |
| Form-Active Ruffling<br>(+) | Surface-Active Ruffling<br>(++) | Section-Active Ruffling<br>(+) | Vector-Active Ruffling<br>(+/-) |

Table 1: A reframing schedule of Structural Systems and Ruffling Techniques

The framework of textiles is divided into three groups of which two are used in the reframing procedure. The first group consists of all textile tectonics. Textile tectonics or textile fabrication are conceived as ways with which textiles are constructed. Crafts like braiding, weaving, knotting and knitting belong to this division.

The second group consists of textile techniques. Textile techniques or textile processing are conceived as ways with which textile tectonics are processed. Crafts like folding, ruffling, pleating and patterning belong to this division.

The third group consists of textile products. Textile products or textile application consists of elements constructed with textile tectonics, textile techniques or a combination of both. This division will be regarded to in the form of case scenarios.

**2.3 Structural Framework; Structure Systems**

For the structural framework, the classifications as described in Structure Systems by Heino Engel is applied. From the six systems described in Structure Systems, four apply well as a

framework for the reframing strategy. The four groups contain Form-active, Vector-active, Section-active and Surface-active systems. In the context of this paper only Form-active systems are used. With a big understanding of form-active behavior in the International Conference on Textile Composites and Inflatable Structures, properties of this structure group will not be discussed in this paper.

### **3 MEMBRANE SHELL GEOMETRY**

In developing efficient structural concepts for architectural use, both engineer and designer have to be willing to work in an interdisciplinary or Mode 2 [8] approach. In architectural design in general, on the one hand architects give importance to form. On the other hand, the engineer will give importance to efficient use of structural elements and techniques. In the application of efficient structural concept, the attention of both parties has to be in equilibrium to result in a satisfying structure or architecture. [7]

In the use of efficient structural concepts like form-active systems, the design process will behave more like a form-finding than a form-giving procedure. Unlike formalist design results like for instance the Guggenheim Museum in Bilbao, in interdisciplinary design, acting players have to cooperate in a heterarchical and transient process without compromising quality. Instead of transposing the structural elaboration to the end of the design process, all parts have to be of same importance during the process with each acting player employing a different type of quality control. [7, 8]

The case scenario as described in this paper is the result of a cooperation of three disciplines, being architecture, civil-engineering and architectural engineering. During the process, each design step was reflected to following steps to come. With the expertise of a vast array of disciplines, mistakes in steps to come could be avoided in advance. In addition to the reframing process performed in this case scenario, every framework was monitored by a matching professional.

#### **3.1 Reframing Strategy; Form-active Systems / Patchwork Techniques**

In the case scenario as described in this paper, a reframing procedure has been performed combining form-active systems and patchwork techniques. Patchwork is conceived as a technique or craft where mostly square patches are composed to a greater cloth. Reframing anticlastic form-active systems into a patchwork framework results in a double curve geometry by smaller square elements. To broaden form-active possibilities, the use of stiff panel materialization was chosen.

#### **3.2 Qualities Membrane-Shell Combination**

With the use of bending resistant panels in a form-active anticlastic structure, shell qualities are introduced. Compared to a form-active pre-tensioned membrane, bending resistant membrane shells yield great potential. In construction, border conditions are less demanding. Since pre-tensioning is less present, boarder details like construction plates and cable details are superfluous. With less pre-tension forces present, supporting structures can be constructed more slender. In materialization, transparent structures in plastics and glass are made possible.

Without complying to efficient material use, flat sheet material can be arranged into form-active systems; surface-active structures evolved into form-active behavior.

#### 4 CASE SCENARIO; BUILDING A MEMBRANE SHELL

To take advantage of the qualities of reflection-in-action, a case scenario is erected to reflect on the theories as described in chapter 3 and 4.

##### 4.1 Geometry

The geometry as described in chapter 3 is materialized in 4 mm wooden multiplex sheet. With the inability of multiplex to bend easily, the double curved had to be converted into a geometry composed by flat wooden plates.

In membrane engineering double curved surfaces are described by a mesh for the minimal surface to be calculated. The mesh used in, for instance, the Force Density Method consists of a non-planar quad subdivision. For a planar subdivision triangles are generated within the mesh. [9, 6]

Using the triangle to describe a double curved surface has great qualities digitally. A vast array of surface distribution is possible and the procedure itself is relatively easy. In fabrication, triangles are hard to deal with. The vertices have a relatively high valence; connection points consist of up to 6 panels. Supporting beam structures consist of a tri-axial geometry. Planar quads on the other hand, have a valence up to four panels with a supporting structure of a bi-axial geometry. [6]

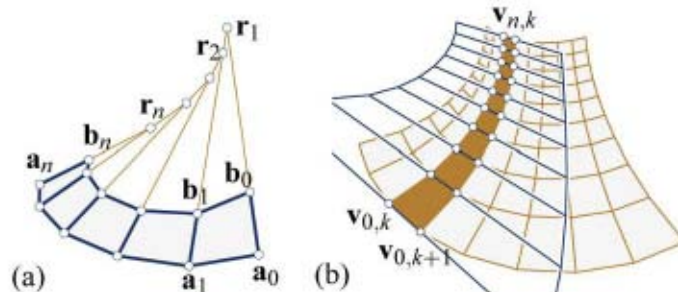


Figure 1: (a); Planar Quad generation by a cone of revolution, (b); Planar Quad generation by a general cylinder surface (Images [6])

Designing with planar quads leaves less flexibility in surface distribution. In [6], two methods are distinguished; Planar Quad generation by a cone of revolution and Planar Quad generation by a general cylinder. The first surface, presented in figure 1a, consists of sections of a triangle, coupled with the connecting surface edge. The latter surface, presented in figure 1b, consist of a strip, built of parallel lines.

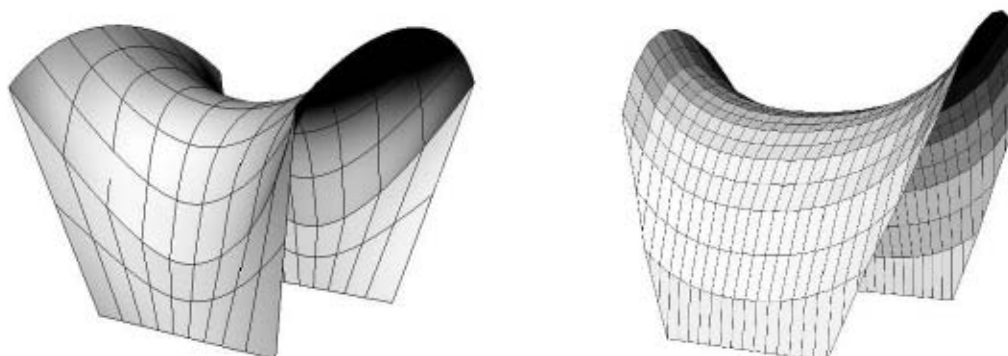


Figure 2: Left; Initial surface design, Right; Design after quad generation

Based on the membrane / shell qualities, described in chapter 3, a design for a canopy was made. Processing this surface with a script running in Rhino3D, a planar quad distribution was generated according to the concept of generation by a cone of revelation. To generate a structure with a balance in an equal surface distribution and a workable tile size, the surface had to be adjusted to meet these needs. To avoid a decrease in panel size in high curvature surface areas, the border conditions of the initial surface design was remodeled to generate a sufficient working surface.

#### 4.2 Materialization

The surface is built from 4 mm wooden multiplex. Wood was chosen because of its accessibility in processing. For the internal connection of the panels several techniques were discussed. With the ambition to create a water tight geometry, two techniques were evaluated for feasibility.

The first technique is a connection by overlap. Layering techniques as used with copper shingles proved to be an interesting surface tectonic. Data like surface layering and angle behavior in this geometry were hard to describe digitally. More research is needed to generate a fluent tectonic by these conditions.

The second technique is a taped connection. By connecting the panels with a tape or adhesive strip, the surface geometry is generated. With the surface geometry remaining intact, minor changes in translation to materialization are notable.

### 4.3 Composite Tape Connections

A tape connection should be able to transfer the internal membrane forces from one panel to the next. Together with the requirement of water tight connection a composite tape connection can be considered. Research has been done on developing this type of connection using Polypropylene (PP), also known as polypropene, is a thermoplastic polymer [11]. Polypropylene has good properties in respect to durability, strength, stiffness and fatigue. It can be woven to form sheets, which in strips connect the panels. The strips are glued to the panels and form a water tight connection.



Figure 3: Woven PP sheet, internal membrane forces

### 4.3 Building Strategy



Figure 4: Panels and Work in Progress

The canopy design consists of an arched wooden boarder structure with panels in between. Like with patterns in membrane engineering, the panels were nested digitally and milled by a CNC machine. Connecting the panels in a fixed sequence resulted in the given geometry.



Figure 5: Membrane Shell Geometry

After finishing the panel assembly, the border geometry was met. The given outline of the supporting structure lined up with the membrane geometry. The form-active behavior was noticeable after closing the shell. Deformation in the shell geometry by loading it locally was the result of bending in the border structure instead of a misfit in geometry.

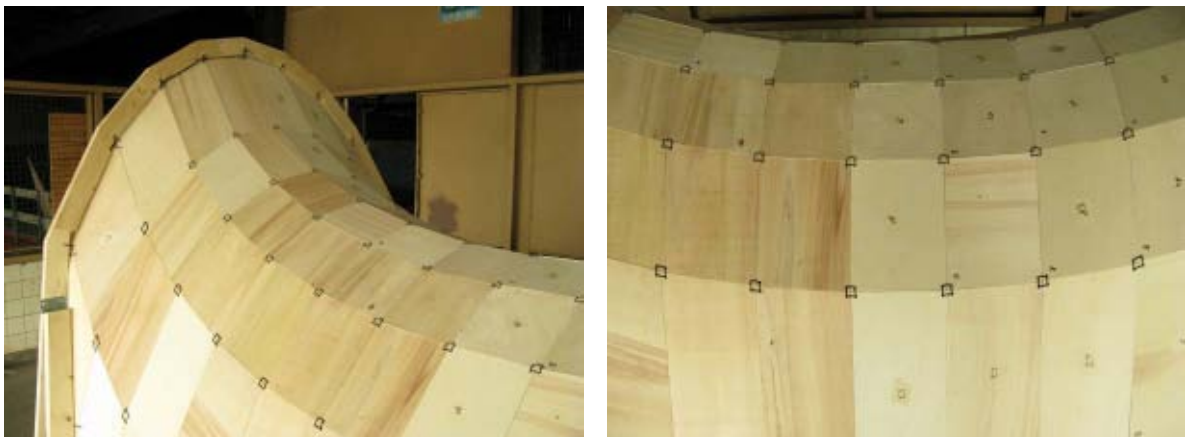


Figure 6: Connections and Surface Tectonics

To tension the structure internally, all panels were interconnected with four tie-rips vertically and four horizontally. The taped connection was not applied because more research in the structural use of taped or adhesive connections is needed.



## 5 STRUCTURAL ANALYSIS

Describing a textile membrane with a shell structure consisting of flat panels, results in a change in structural behavior of the geometry. To reflect the difference in structural behavior of the form-active geometry in different “discretization” stages, a brief Finite Element study is performed. The three different discretization stages are:

- Continuous shell form-active shape
- Continuous shell discretized with planar quads
- Discontinuous shell discretized with planar quads interconnected in the corners with hinges.

The study focuses on the structural response of the different structural systems.

### 5.1 Description of models

A numerical simulation of the above described models is performed with the finite element software Abaqus (version V6.10.EF). The models consist of quadratic quadrilateral elements with a edge size of approx. 50 mm.

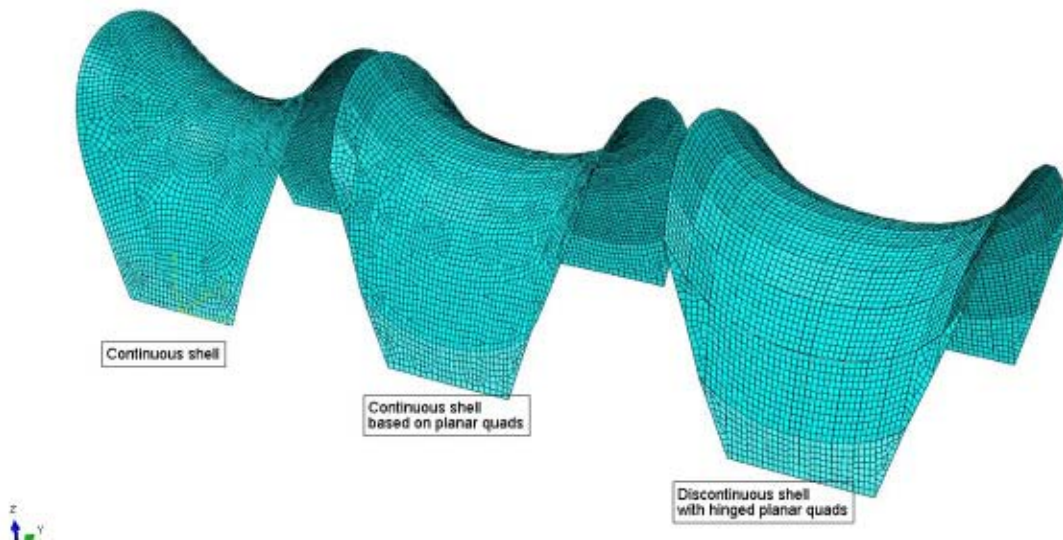


Figure 7: Model plot with mesh of the three models

To stay close to the geometry as built, the material used in the model is the equivalent of wood with a modulus of elasticity of  $9000 \text{ N/mm}^2$  and a shell thickness of 4 mm. Instead of simulating the exact behavior of the individual wooden panels, an idea of the differences in global behavior of the three structural concepts was obtained. Herewith no material non-linearity's have been included. As with the built scenario, the three translational degrees of freedom along the edges of the shell models are set to zero.

For the structural response study three different load cases have been reviewed:

- Symmetrical: gravitational load ( $9.81 \text{ m/s}^2$ )
- Symmetrical: vertical concentrated load in the middle of the shell structure (100 N).
- Asymmetrical: horizontal pressure load on one side of the shell ( $100 \text{ N/m}^2$ ).

### 5.3 Discussion of results

As to be expected, both continuous shells react quite differently compared to the discontinuous shell. The capability of the continuous shells to transfer the applied loads more evenly to the boundary conditions makes both shells more rigid.

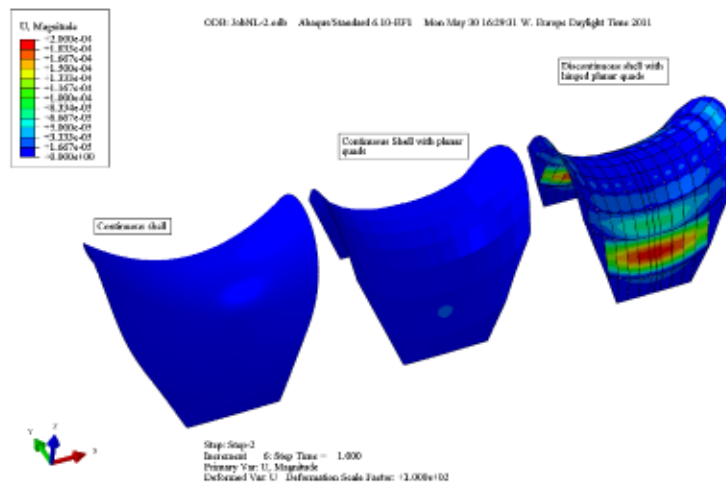


Figure 8: Overview of deformations of the three models ; gravitational loads (in m)

In figure 7 the differences of the three structural concepts are shown for the gravitation load. The deformations of the discontinuous shell is 4 times higher than the continuous shell with planar quads.

The continuous shell has a ideal shape. This geometry combined with the bending stiffness of the material make it a very stiff structural geometry.

The deviation of this ideal shape by discretizing it with planar quads, still results in a stiff shape. The folding lines in between the quads are areas with more stiffness and attract more loads. This clearly shows on the stress plots of the structure under gravitational load as presented in figure 8.

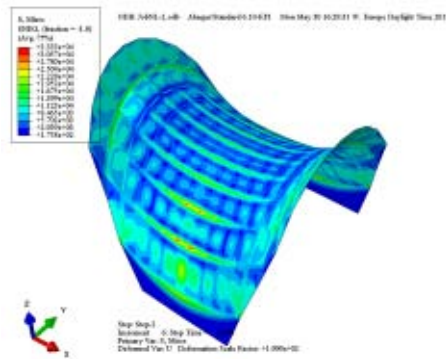


Figure 9: Stress plot of continuous shell with planar quads with gravitational load (in  $N/m^2$ )

The discontinuous shell acts like a “net”; coupled plates, kept in shape by its boundary conditions. Globally the surface has no bending stiffness and acts like a textile membrane. Due to the local bending stiffness of the panels and the hinged connections, the panels start rotating out of plane when loaded asymmetrically. This somewhat unstable behavior is shown in figure 10 (scaled deformations).

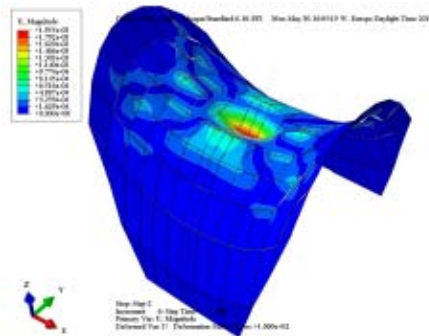


Figure 10: Deformation of discontinuous shell loaded with a concentrated load in the middle (in m)

In both the shells materialized with planar quads, the quads will experience local bending in between the folding lines, when loaded with a surface pressure (figure 10; plots with different deformation scales).

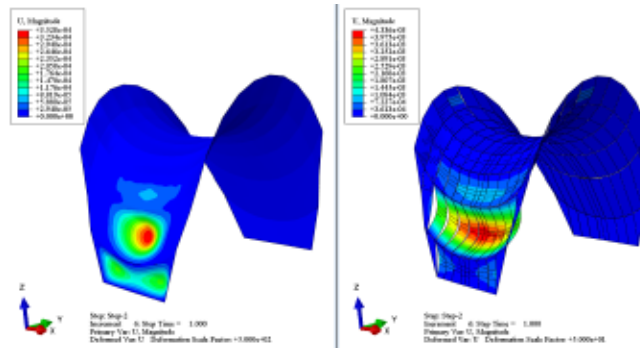


Figure 11: Local bending of planar surfaces (deformation in m)

From this brief study on the structural behavior of different discretizations steps, it can be concluded that further study of form-active shells consisting of planar quads should involve the development of edge connections between the quads to be able to obtain a shell behavior. Given this connection the geometry should behave more like the continuous shell with planar quads.

## 12 CONCLUSIONS & RECOMMENDATIONS

Reframing textile techniques into form-active systems yields great qualities for both structural use as material application. The construction of a membrane bending-resistant anticlastic shell proved to be an interesting addition to membrane structures. In materialization, broader possibilities in surface tectonic are provided. In structural use, efficient materialization can be obtained with bending resistant flat sheets. More research is needed in the sheet connections. To obtain a durable watertight surface, research has to be done in tape or sealant. To obtain a hybrid structural integrity, research has to be done in for instance composite tapes or textile adhesives. As a start this mesh layout was chosen. In further research the mapping of a quad mesh over the desired shape by conforming techniques could be investigated.

## REFERENCES

- [1] D.A. Schön, *The Reflective Practitioner*, Basic Books, 1984
- [2] N. Cross, *Designerly Ways of Knowing*, Birkhäuser, 2007
- [3] H. Dunin-Woyseth and Liv Merete Nielsen, eds., *Discussing Transdisciplinarity*, The Nordic Reader, 2004
- [4] Comparing Paradigms
- [5] H. Engel, *Structure Systems*, Hantje Cantz, 2007
- [6] H. Pottmann, J. Wallner, S. Brell-Cokcan, *Discrete surfaces for architectural design*, TU Graz, Institut für Geometrie, 2007
- [7] Y. Weinand, *Innovative timber Constructions*, Journal of the International Association for Shell and Spatial Structures, **50**, 1028-365X (2009)
- [8] M. Gibbons, eds., *The New Production of Knowledge*, Sage Publications, 1994 (2002)
- [9] D. Ströbel, P. Singer, *Computational Modeling of Lightweight Structures*, technet-GmbH.com
- [10] F. Otto et al., *ILI – IL41*, Published by Institute for Lightweight Structures
- [11] D. Vosmeur, *De ontwikkeling van een scharnierende verbinding tussen sandwichpanelen (The development on a hinged connection between sandwich panels)*, Delft University of Technology, 2006