FROM MEMBRANE FORM TO RIGID SHELL

The topic of how to stiffen fabric structures respectively converting flexible curved structures into rigid shells is not a new one. As early as the 1950s and 60s, Heinz Isler amongst others, experimented with new form finding methods to freeze wet, hanging and draped textiles (Fig. 1). He developed a unique, detailed and very practical approach to generate uncommon structures. Likewise his pneumatic experiments and the resulting "Buckelschalen" show his elaborate technique of utilizing soft forms to build concrete shells. Another example is the Philips Pavilion for the Brussels Expo in 1958 which was designed by Le Corbusier and Yannis Xenakis (Fig. 2). The geometry was built up from conjoining hyperbolic paraboloids. The surface which started as sand hills divided into quadrangles by a grid of casing planks and consequently placing reinforcement meshes into the mould, were casted with concrete. The $1.5m^2$ large and 50mm thick prefabricated panels were numbered, transported to site and re-assembled. The primary loadbearing structure was made from a set of beams that defined the borders and ridges of the structure and a combination of steel rods and a cable net structure upon which the panels were mounted. In contrary to the ephemeral icing approach of Isler, Frei Otto solved the conversion problem from flexible to rigid with his IL-Institute building in a more enduring way (Fig. 3). The flexible cable net structure initially designed to hang a fabric underneath (for the Expo Montreal 1967) was converted to carry a rigid multilayer roof construction made up of wooden slats and slate shingles that followed the initial tensile form. This method was very labour intensive and required sophisticated and skilled craftsmanship. Another technique of conversion was used at the Multihalle Mannheim ("Bundesgartenschau" 1975). The conversion and inversion of a hanging form into a compressive grid-shell structure was achieved by lifting up a wooden lattice construction to a given position, fixing the borderlines and locking the lattice joints. A PES-PVC fabric was cut, connected to the structure and welded on site (Fig. 4).

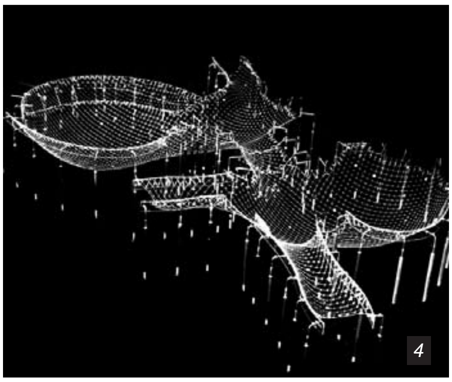


Figure 1. Ice structure by Heinz Isler
Figure 2. Philips Pavilion in Brussels by Le Corbusier © wikimedia commons / Wouter Hagens
Figure 3. Inside view of the IL-Pavilion by Frei Otto © ILEK/Uni Stuttgart
Figure 4. Hanging model for the Multihalle Mannheim

APPLIED RESEARCH ON MATERIAL AND PROCESS TECHNOLOGY TO APPLY AND STIFFEN MEMBRANE STRUCTURES WITH SHOTCRETE.

Institute for Membrane and Shell Technology - IMS

The comprehensive interest for membrane and shell structure was the reason that Prof. Robert Off, Director of the IMS e.V. Dessau, initiated a research project with the research objective to „develop a method to harden mechanically pre-stressed membrane structures by spraying them with concrete – fabric used as reinforcement and as dead formwork". Our overall goal was to use mechanically pre-stressed fabric structures, on behalf of formal approach and structural behaviour and spray them with concrete. Beside the research of the material technology, an important structural question was how to activate the pretension within the membrane to optimize the load bearing behaviour of the overall composite structure.

The IMS, which is an associated Institute of the Anhalt University of Applied Sciences in Dessau, has been teaching and researching in the field of membrane structures since 1999. Among others innovative approaches with foam/hardened composite fabric structures were elaborated.

Together with a partner for the membrane fabrication tasks (Stegmaier Zelte) and a partner for concrete restoration respectively expertise for shotcrete (Lenz&Mundt), an interdisciplinary team was formed and a foresightful research was conducted. The funding came from the Federal Ministry for Economic Affairs and Energy respectively from the AiF (German Federation of Industrial Research Associations). "As an industry-driven organization, the AiF aims at initiating applied research and development for small and medium-sized enterprises, as well as qualifying the new generation of academics in innovative fields and organizing the distribution of scientific knowledge. Furthermore it is intended to turn ideas into successful products, processes or services in the market."

Material testing and composite development

Starting point was the evaluation of the material properties to get an in-depth understanding of each material component. Different cements and strength classes, additives and maximum grain size categories were evaluated. With compression tests on cubical specimen, splitting tensile strength on cylindrical specimen and three-point-flexural-tension tests on prismatic specimen, we surveyed the compressive stresses and ductility of the concrete. Second step was the evaluation of the fabric material. Beside the physical parameters, the main focus was on the chemical resistances (NaOH, H_2SO_4, Paraffin, NaCl, $MgSO_4$ and K_2CO_3). The applicability of the different yarn materials, coating material as well as the size of the mesh openings and the weaving styles had to be assessed. Beside the technical values the properties concerning the processing and workability of the materials were of high interest.
With the same testing program as for the individual materials we surveyed the composite behaviour. In this stage of the research we took the influence of the level of pre-stress in the membrane layer (uniaxial as well as biaxial) into consideration. Special specimens were developed and the testing rigs had to be modified. With the three-point-flexural-tension testing we succeeded to record the characteristic material curve which was used to setup a model in a FEM Software (Fig. 5).

Simultaneously to the investigation of the laboratory specimen, we executed spraying trials within “real” conditions to adjust the parameters (type of spraying, pressure, water-cement-ratio, distance and angle of the gun nozzle to the membrane) of the spraying process. From these trials we retrieved numerous samples and identified a big difference in the values between the “handmade” laboratory specimen and the sprayed specimen. Due to the parameters of the spraying process and the so called “Rückprall” (the bouncing back of particles when they hit a surface) the applied concrete mixture differs from the initial mixture that is provided by the producer and was used for the lab-specimen.

Prototyping and evaluation

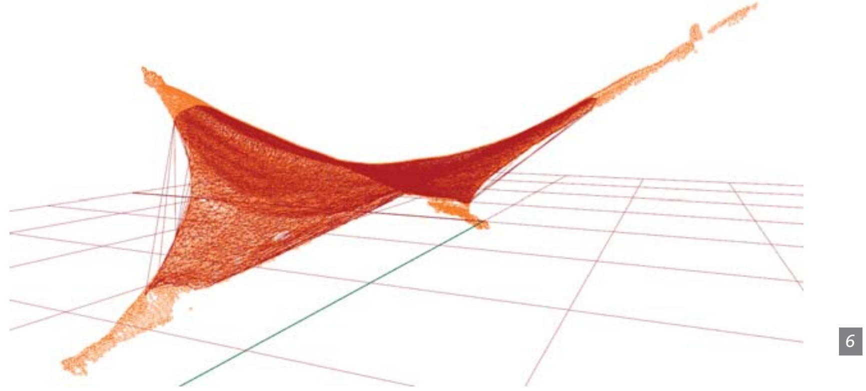
With a sail setup we started the evaluation of the findings from the material testing. The elaboration of the spraying process, the construction details and the overall structural behaviour was the focus in this stage of the research. For simplification reason our first structure was a 4 point sail with cable edges (3m x 3m). 3d scans of the upper and lower side of the sail structure revealed the structure´s property to move and the insufficient level of pre-stress in the membrane caused a kind of ponding, hence a very uneven thickness of the sprayed concrete layer could be noticed. In close collaboration with the Institute of Geoinformation and Surveying a very detailed deformation analysis was executed. Results and the applicability of the photogrammetric versus the 3d scanning survey during static and dynamic load tests were evaluated (Fig. 6). This first large scale attempt was very fruitful in detecting the real problems of the spraying process and helped to improve the design of the structural details.

With the realization of the final prototype we wanted to gather more detailed knowledge while getting as close as possible to a real building situation. Curvature, usability, cost, testing facilities (also for the long-term behaviour) were taken into account for the design task. The geometry of the prototype is described by an anticlastic surface between 3 high points and three low points with rigid edges and ridgelines in the surface. It is 4.5m in height and 6.2m (at the highpoints) in diameter, and consists of the following building components:

- three steel A-frames (plus foundations) from HEA beams,
- three stay cables (plus foundations) with tensioning fittings,
- three ridge cables meeting in the central point of the surface.

The steel frames were connected to the foundations with hinged supports to allow movement for mounting and pre-stressing and for measuring the cable forces. In the axis of each stay cable we implemented two units for tensioning as well as a load cell to control, define and monitor the cable forces. From the preliminary large scale tests and the material survey we could develop a catalogue of specifications and hence decided for a steel fibre reinforced shotcrete and an open mesh fabric (Fig. 7a - b).

For a future application we decided to apply the concrete in more than one step. For large scale projects a first thin layer should give the structure enough stiffness to allow craftsmen walking on the structure for the following application steps. The second layer should guarantee the end rigidity of the concrete shell. The third and last layer was intended only for the final surface appearance. A smoothing treatment by hand was executed to seal the surface and prevent water and dirt from sticking on the surface. For an optimal bonding and adhesion of the shotcrete layers each layer was sandblasted before the next spraying application. Loose grain material was removed and cracks were “opened”.
During the building process we executed various 3d scans to evaluate the geometry and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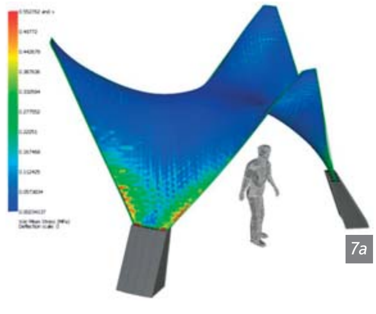
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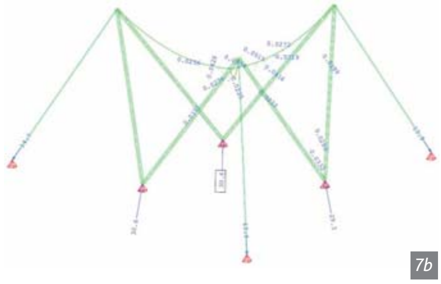
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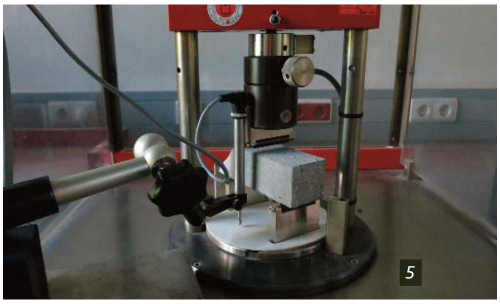
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Figure 5. 3 point flexural tension testing rig with external displacement transducer

Figure 6. Evaluation of the geometry of the 4 point sail structure from a 3d scanning survey

Figure 7a - b. Digital model (Mises Stresses) and reaction forces tested how well the digital model and realised structure matched. Specimen from the onsite spraying were taken to the lab and compared to the assumed values. Cable forces were constantly monitored and adjusted according to the specifications.

The structural behaviour was observed during mounting of the fabric structure, spraying and hardening process of the concrete (Fig. 8). The verification of the various results and the merging of all parameters was challenging but also very promising. The comparison between the digital model and the real prototype gave various surprising findings and a holistic knowledge of the structures properties and behaviour (Fig. 9 - 10).

One key issue when applying the shotcrete was to guarantee an even distribution of the sprayed concrete. The geometry of the edge beams helped to define the layer thickness at least close to the edges. The thickness in the inner surface areas had to be monitored and manually adjusted by the skilled craftsman.

By matching scans from the upper and the lower surfaces and processing them, we could evaluate the variation of the layer thickness (Fig. 11). Even though the specifications were held, a perspective for future structures could be to adapt and optimize the control of the layer thickness.

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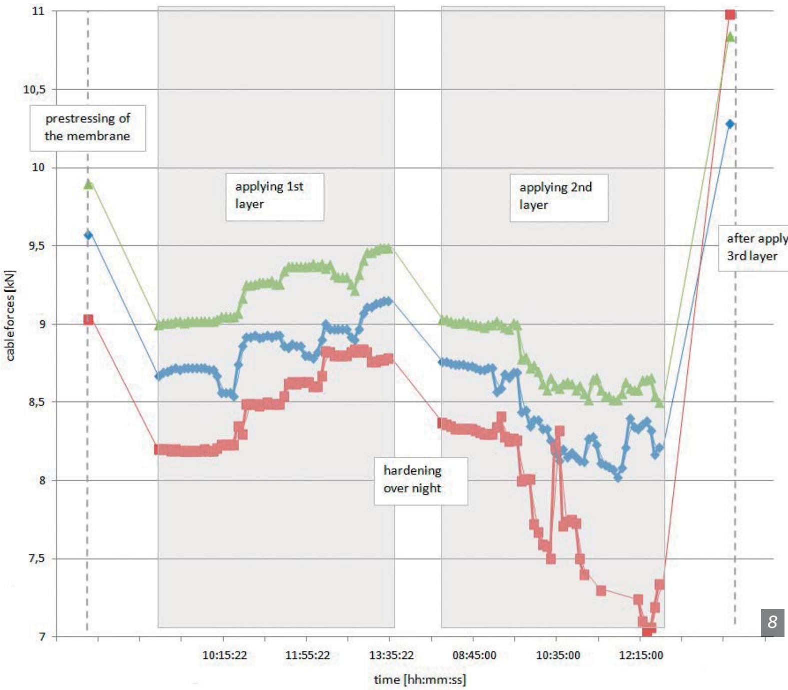
Conclusion - call to cooperate

Even though not all of the intended findings are fully evaluated yet, the outcome of the research project is satisfying and gives a perspective towards further research objectives.

- From large scale load tests as well as the simple material tests with specimen extracted from the shell, we expect a comprehensive knowledge of the structural behaviour of the prototype.
- The long term behaviour of the composite (durability of bonding and the membrane material) will be evaluated.
- Questions regarding the design, the scale and economic matters of the shell structure are going to be investigated.

Therefore we are very much interested in cooperating with new partners to proceed and extend this research. Aside from this topic, further research in the field of textile and polymer façade structures are just about to be launched at the IMS. However we are also open for your research proposals. For further interest or discussion please do not hesitate to contact us via www.ims-institute.org.



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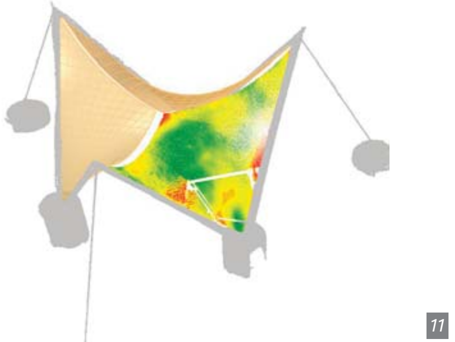

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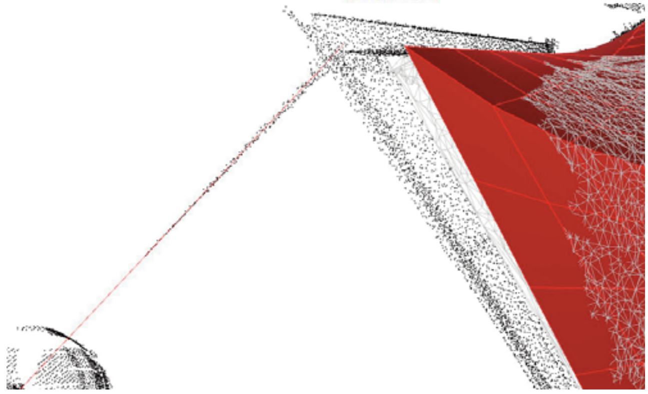

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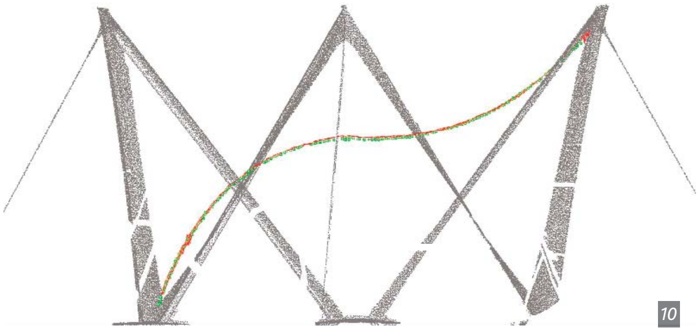

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Figure 8. Monitoring of the cable forces during spraying and hardening process

Figure 9. Matching of the digital "formfinding" model (red) and the 3d scan (grey)

Figure 10. Deflection of the lower shell surface after spraying (green) compared to the plain prestressed membrane structure (red)

Figure 11. Evaluation and supervision of shell thickness from 3d scanning survey Range of thickness from 30mm (green) up to 70mm (red).

Figure 12. Final Prototype

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