STRUCTURAL MEMBRANES 2021

X INTERNATIONAL CONFERENCE ON TEXTILE COMPOSITES AND INFLATABLE STRUCTURES

The "Tenth International Conference on Textile Composites and Inflatable Structures" was held online in September 2021, organized by the International Centre for Numerical Methods in Engineering (CIMNE) and chaired by K. U. Bletzinger (TUM), E. Oñate (UPC), R. Wüchner (TUM) and C. Lázaro (UPV). It was the tenth of a series of symposiums that originated in Barcelona in 2003, but unfortunately the event was not face-to-face, thus without meetings, contacts, coffee-breaks, gala dinner and technical visits. Hopefully, in the next edition, to be held in Valencia in 2023, normality will be restored.

At the two-day conference, 6 plenary lectures and 73 presentations in 14 sessions were given to 99 participants.
https://congress.cimne.com/membranes2021/frontal/Objectives.asp

PLENARY LECTURES

Katja Bernert from Mehler Texnologies started the conference with her plenary lecture: "Transforming textiles to testimonies". She talked about the problem of recycling the materials used in the manufacture of membranes. In recent years, there has been a short success when it comes to solutions for recycling vinyl coated polyester fabrics. The separation of glass fibres from PTFE coatings is not yet solved sufficiently and, on the other hand, clients and industry are not willing to spend money on recycling or reusing material. At the same time the weaving and coating industry developed material with extended durability weakening the need to find immediate recycling solutions. Other approaches could be the use of recycled raw materials (not necessarily from used membranes), specific actions such as urban healing skins (Fig. 1), maintenance, inspection, cleaning or to find regulations that prescribe the use of a certain ratio of recycled material. As in other areas too, a binding commitment might be the only solution to bring forward recycling processes.

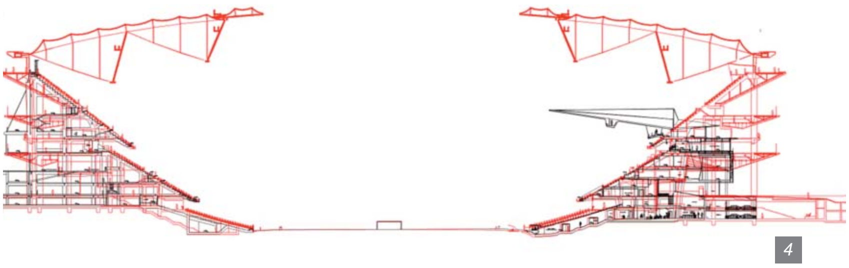
Improving the efficiency of membranes was also the topic of Josep Llorens from the Technical University of Catalonia. In his lecture "Appropriate design of structural membranes" he found that although design tools have progressed considerably, some membrane structures are still designed without taking advantage of their structural characteristics.

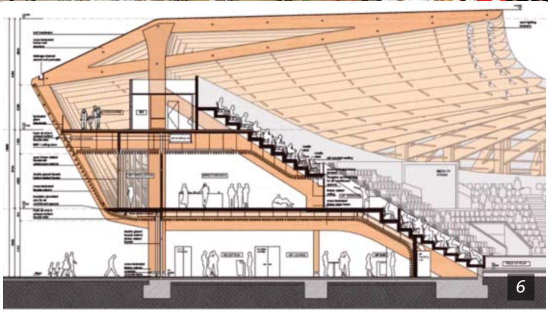
The result is usually a disproportionate steel structure that is cladded to generate an (arbitrary) projected shape. In order to achieve a good result, he (highly) recommended to respect the principles of only tension, funicularity, curvature and pre-stressing, as well as to take advantage of the available design methods to properly determine the form (in equilibrium), the loads and the hybrid behaviour of the structure. The most significant variables can also be parameterized, just as bending avoided in the supporting structure and compression optimized (Fig. 2). Several improvements have been introduced that can be investigated further and best practices could be looked up.

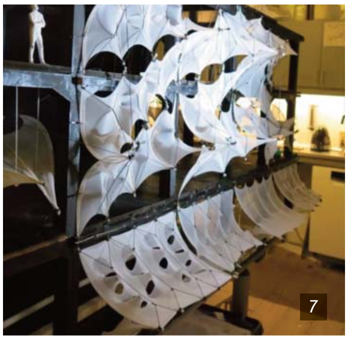
In the third plenary lecture, Helmut Pottman from the Centre for Geometry and Computational Design KAUST, Saudi Arabia, gave a master class on geometry applied to grid shells for the design of architectural surfaces from flat quadrilateral panels (Fig. 3). The design process of so called "free" form surfaces includes a feasible segmentation (discretization) into panels. A basic, convenient and structurally stable way of representing a smooth shape in a discrete way is the use of quadrilateral meshes with planar faces, that tends to have less weight than triangular meshes [1]. It should be noted that all the treatment was only geometric. The structural behaviour was not analyzed, so there is the possibility that the surface obtained is not feasible with a tensioned membrane.

Figure 1. A second skin façade reduces nitrogen oxide pollution. Aachen Central Bus Station.

Figure 2a/b. Two different approaches to design the support of a membrane.







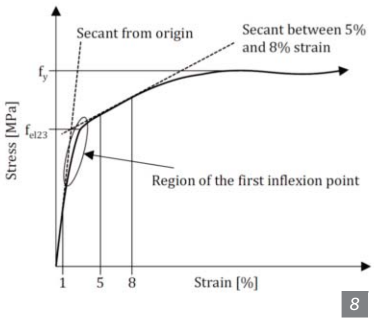


Figure 3. Architectural surfaces from flat panels (Helmut Pottman).

Figure 4. Nou Camp Nou, Barcelona, sbp. (black=existing, red=new).

Figure 5. Demountable and transportable Stadium Ras Abu Aboud, Qatar, sbp together with Fenwick Iribarren Architects and Hilson Moran.

Figure 6. Zaha Hadid Architects with sbp: Forest Green Rover Stadium entirely built of wood and other environmentally friendly materials.

Figure 7. Model study for the installation of knitted membranes, CITA, Denmark.

Figure 8. Simplified method to determine the elastic limit in a uniaxial stress-strain path.

In his presentation: "The lightweight principle - An important key for embodied carbon reduction in construction", Knut Göppert from sbp referred to 5 strategies to improve the sustainability of large span structures. The first strategy is lightness to save material as the top priority, with special mention to the spoke wheel system. For the new stadium of the Tottenham Hotspurs FC, the cable roof provided a 12% weight reduction versus the solution based on trusses and cantilevers. The second strategy is to resort to modernization rather than demolition, as demonstrated in the Mercedes Benz Arena, the Kiev National Stadium and the Berlin Olympic Stadium, among others (Fig. 4). Multifunctional use is the third strategy enhanced by the retractability of the roof, and the fourth is to give stadiums more than one life. It is the case of demountable stadiums, very suitable in cases where smaller venues are needed (Fig. 5). And the use of timber provides the fifth strategy (Fig. 6). He concluded that membranes will be the perfect material for roofs and façades.

Mette Ramsgaard Thomsen from the Centre for Information, Technology and Architecture (CITA), Denmark, explored the possibilities of knitted membranes in architecture. She discussed emerging methods for predicting the material behaviour of functionally graded membranes using knit as a method of locally tuning the performance. Starting from the textile systems and hybrid structures examined by CITA across the last 10 years, she addressed the form finding, simulation and fabrication to create highly bespoke membranes that incorporate detailing and change knit structure detailing to shape the performance. Prominent examples were the hybrid tower installed in Guimaraes, the Isoropia pavilion in Venice and the installation in a large hall of an old factory (Fig. 7).

The last plenary lecture was given by Natalie Stranghöner from the Institute for Metal and Lightweight Structures, Essen: "European ETFE-design. New findings and concepts". She aimed to give an insight into the ongoing development of standardization and research activities for foil structures. With the publication of the Technical Specification prCEN/TS 19102, the European Committee for Standardization (CEN) will provide a European standard for the design, analysis and execution of buildings and structural works made with structural membrane materials. This includes many kinds of tensioned membrane structures, including fabrics as well as foils in general and ETFE foils in particular. The safe and economic design involves an understanding of the material and seam behaviour. For this purpose, she gave an overview on different research projects which examine the short and long-term behaviour of ETFE-foils and their welding. Subjects of these projects are the tensile, creep and relaxation behaviour of the base material under uniaxial and biaxial stress ratios as well as the tensile behaviour of the weld seams and the optimization of the welding and testing procedures (Fig. 8).

Figure 9. Sequence of the modeling with combined pneumatic and mechanical stressed structures.

NUMERICAL METHODS AND MODELING

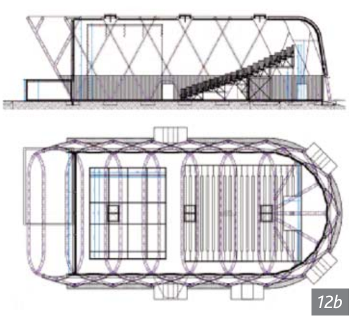
This session is the one that received more contributions. Jürgen Holl from Technet participated with: "Fast model generation and static calculation of combined pneumatic and mechanically stressed structures". The generation of models and static calculation of combined structures are often a challenge because mechanically stressed membranes need form finding calculation. The geometry cannot be fixed arbitrarily because internal forces or stresses and the surface geometry are not independent of each other. It is not the case of pneumatic structures whose shapes can be created sometimes by geometric functions such as spheres, cylinders and torus. When combining mechanically and pneumatically stressed structures, a particular difficulty in model generation is the intersection of individual volume elements. To avoid the intersection problems in the case of discrete meshes, Nurbs surfaces can be used and intersected. The newly created partial surfaces as objects are combined and then discretised. This results in topologically correct mechanical models that are suitable for a static calculation (Fig. 9).

DETAILING - CASE STUDIES - INSTALLATION

Katja Bernert from Mehler Texnologies started this session with "A travel guide to textile architecture" showing recent textile architecture projects highlighting a school and a resort. The Green School campus in New Zealand is described [2] as a "collaborative design based on organic materials in order to function sustainably and provide students with a shelter nestled amongst nature. Curved shapes are predominant to create an atmosphere that supports alternative thinking. The learning pods are built with light materials and surrounded by native plants in an inspirational environment for the students to think openly and creatively, while enjoying all aspects of the exquisite outdoor setting" (Fig. 10). In a more playful way, she also mentioned the Thorntree River Lodge, Zambia (Fig. 11).

Nicolas Pauli from the Laboratoire Innovation Forme Architecture Milieux (LIFAM), School of Architecture of Montpellier described the design, fabrication and erection of the permanent circus tent with rock wool isolated tensile roof of the National Circus Centre "SIRQUE" installed in the heritage site of the castle of Nexon (Fig. 12). The size of the circus tent is 40x18x11m. The surface in plan is 650m^2, the surface of the membrane is 1.100m^2 and its form is "cylindrical" with an end in a quarter of "sphere". Its structure is composed of 7 arches and 5 half arches made of steel. The envelop is based on the use of 2 textiles skins with a distance of 300mm, including a 140mm rock wool insulation layer (U=0.2 W/m^{2}K) in between, naturally laying on the internal membrane, and just maintained in place by straps. To avoid condensation venting areas have been designed. The membranes are laced all along their peripheral edges on upper and lower tensioning beams upon a Ø33mm CHS. Notably, in order to avoid moisture pass through from the inside of the building into the rock wool, the internal skin has been waterproofed manufacturing it in only 1 piece of 1.100m^2 creating a watertight barrier between in and out.

Gerd Schmid from formTL exposed: "Infrastructure buildings – New design language for urban architecture: Bus stations, tram stations, transfer hubs". He introduced the problems of the roofs in public spaces that are rarely cleaned. The glazing and the colour-coated metal roofs become dirty. Pigeon defence spikes are stuck to lattice girders in which paper cups, bird feathers and gray cobwebs collect. The buildings fulfil their intended task inadequately because lack of care provokes negligent behaviour and the public places become more and more inhospitable. In addition, construction is often carried out with open profiles on which a lot of dirt is deposited. As a result, these roofs often look neglected. As a solution, materials that have less adhesion can be used. For example anodized aluminium, ETFE foil, circular hollow sections with no landing places for pigeons and corrosion protection (Table 1).



form TL design compared with common design	Common designed High maintenance needed Short term visual quality	Enhanced form TL design Little maintenance. Long term visual quality
Profile	Open profile	Hollow section
Girder	Girder truss. Space frame	Single beam
Envelope	PVC coated polyester Membrane with acrylic finish Glass sheets	ETFE or PTFE Anodized aluminium
Combination	Exposed structure	Covered structure
Corrosion protection (profiles)	C3-C5 M (5-15 years)	C3-C5 VH (>25 years)
Corrosion protection (ropes)	Hot dip coated steel wire	Stainless steel Galfan coated wire Aluminium coated wire

Figure 10. Boon Architects, 2020 Green School, New Zealand.

Figure 11. Thorntree River Lodge, Zambia (courtesy of Mehler Texnologies).

Figure 12a/b. ADH Architects with Abaca, VSO and SIRC, 2021: "SIRQUE" National Circus Centre tent, Exon.

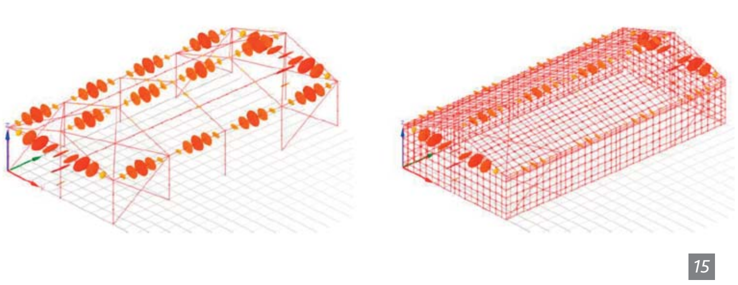
Table 1. formTL design compared with common design of bus stations

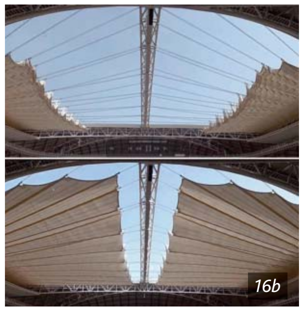
Figure 13. formTL: Bus Terminal, Sursee.

Figure 14. Seam test carried out with foil exit angle of 15º.

Figure 15. The flexibilities of the ridge and eave purlins are far bigger in the conventional calculation (left). The membrane stiffens the steel structure (right).

Figure 16a/b. Zaha Hadid with Maffeis and Pfeifer, 2019: Al Janoub Stadium, Al Wakrah.





On the other hand, table shapes can be adopted to be freely adapted to floor plans. Together with the visual lightness, the interaction between artificial, natural light and the colour of the sky creates a good and friendly atmosphere on site supported by the cleanliness and quality of the materials (Fig. 13). This design language is not only suitable for mobility buildings but basically for all types of buildings in public spaces, where it is important that architecture creates identity and where the town administration often forget to look after their buildings.

Andreas Kunze from the Deutsche Institute für Textil und Faserforschung, Denkendorf, introduced the "Integration of ETFE foil cushions into conventional glass facade systems by means of adapted, space-saving joining methods". The current technology for producing a translucent facade is dominated by glazing, facade construction kits and a high degree of prefabrication. A new technology was discussed, that allow the integration of ETFE foil cushions into conventional, customary, modular glass facade systems on the market. A new facade element was presented, which consists of a rigid profile frame with integrated thermal separation, covered on both sides with ETFE foil. New edge formations have been developed and tested with regard to the industrial prefabrication of rectangular ETFE facade cushion elements. In particular three space-saving joining methods for joining ETFE foils with aluminium profiles were presented and discussed: gluing with cyanoacrylate adhesive, welding onto an ETFE coating and clamping in a mini keder, as well as the associated, necessary pre-treatment methods. An assessment of the joints was made through tensile tests (Fig. 14) and long-time outdoor weathering tests. All methods were applied in demonstrators. He concluded that all methods represent technical solutions and, with regard to recycling and reuse, the clamping process offers easy material separation. The glued foils can also simply be peeled off and the profiles cleaned by sandblasting. So far, the ETFE coated surfaces can only be welded over. The welding technology is particularly interesting for the automatic covering of frames in a production line.

Dieter Ströbel from technet addressed the calculation of textile halls. He stated that the calculation of textile membranes should never be carried out independently of the primary support structure. The separation of the membrane and the primary structure, with the reaction forces applied as external loads, results in significantly higher steel consumption and is therefore uneconomical. The idea that the savings from the hybrid calculation (i.e. the calculation of the membrane and the primary construction together) are only given for double-curved membrane surfaces was refuted because even with straight membrane surfaces, as they are usually present in textile halls in general, smaller cross-sections are obtained for the primary construction through the coupled or hybrid calculation. Nevertheless, these more accurate models are little used in practice because their generation is time-consuming and not all requirements can be represented in usual software packages. In particular, membrane panels that are not firmly attached to the steel or aluminium elements, but rather membrane surfaces that slide over them, are a problem. He showed that a fast modelling under consideration of sliding conditions yields results that are below the usual deformations and metal quantities (Fig. 15).

"Structural membranes in motion" was the contribution of Thomas Hermeking from Pfeifer. He started listing the elements of retractable structural membranes that are cables, sliding trolleys, winches, membranes and operation and control systems. He mentioned several examples, highlighting the main characteristics of the Al Janoub FIFA World Cup Stadium retractable roof. It is a unique combination of structural cables and membranes in motion, with a surface of 12.000m^2. It consists of two halves that close on a central girder with a combination of cables and membranes reinforced with belts in a widening geometry that created new challenges for the driving system never faced before. The lines have been arranged in a “V” shape by means of non parallel valley and ridge Ø55mm cables connected to the central girder (Fig. 16). The trolleys of the driving system travel on rails that are not straight, but slightly arched with different lengths, different levels, different slopes and changing distances between the grid lines. 50 Winches have to be synchronized for moving and tensioning the panels up to 200kN. An advanced driving system with maximum control flexibility to move the membrane smoothly and tension it correctly has been needed. Additional requirements were the extreme environmental conditions (high corrosion, high temperatures and sandstorms) and minimized visual impact of the mechanical system, meaning a reduced number of catwalks and grating, together with tensioning the membrane with winches instead of hydraulics.

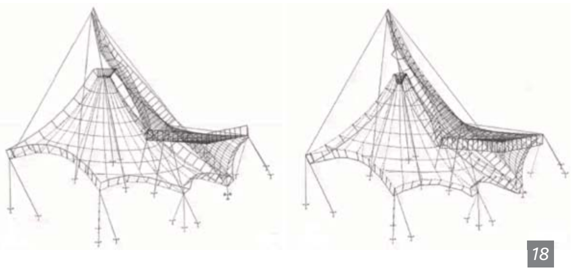


Figure 17. G. Capellán with Arenas & Asociados and Lastra & Zorrilla, 2003: Alicante Cruise Terminal.
Figure 18. Uniform wind load: pressure (left), suction (right).
Figure 19. A. de Palacio & F. Arnodin, 1893: Bizkaia Bridge, Getxo.

MASTS

Structural membranes rely on tension, but their supports are structures under bending or compression that are much less effective. Bending may be avoided as much as possible, but there is almost no choice but to grapple with compression. That's why it is of greater interest to deal with masts which are the compressed members par excellence.

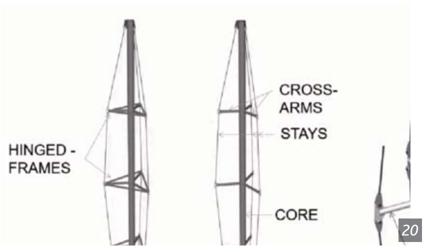
Santiago Guerra from Arenas Asociados drew attention to the design of masts with the example of those that support the textile roof of the Alicante Cruise Terminal (Fig. 17). It consists of a hyperbolic paraboloid overlapping a conoid around a main mast (33m high, Ø619x16mm) tensioned by 6 secondary masts (5 to 11m high, Ø170x10 to 219x10mm) and anchor points through Ø22mm cables. The footings receive the masts and act as counterweights to tension anchors. They are braced by beams to resist seismic actions. The simulated wind load (pressure and suction) was uniform, independent of the deformations, with values from 1kN/m^2 up to 30m high to 1,25kN/m^2 beyond (Fig. 18). Covered surface: 460m^2; Material cost (2003) 315.000€; Bidding cost 450.000€ = 975 €/m^2 (VAT included).

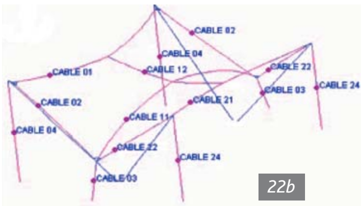
Bruce Danziger in his lecture: "Elegant Mast Structures" explored the creative structural engineering design process for elegant mast structures. He was amazed by some achievements of the past such as the Shukov tower in Moscow 1922 and the transporter bridge in Marseille 1905 similar to the first one in Getxo (Fig. 19). He mentioned the Travel and Transport Building of the Century of Progress Exposition in Chicago 1933, the Trylon, Perisphere and Helicline of the World of Tomorrow in New York 1939, the Skylon of the Festival of Britain 1951, Miguel Fisac, Robert le Ricolais, the Yoyogi National Olympic Stadiums 1964 and the Batcolumn in Chicago 1977 among others. He also mentioned more recent examples in which he participated including the Pavilion of the Future at the EXPO '92 in Sevilla, the Sony Center Forum Roof in Berlin and the Tropical Rainforest Greenhouse of the Taichung Botanical Gardens.

Large cable-stayed masts were the topic of Sudarshan Krishnan from the University of Illinois at Urbana-Champaign. Their structural merits lie in the reduced core size and high compression strength derived from the use of prestressed stays attached to crosstrees (Fig. 20). They have been used in iconic stadia structures such as the Algarve stadium in Portugal designed by HOK (Fig. 21). Its roof is suspended above the seating to allow for uninterrupted spans and views for the spectators by means of four majestic steel stayed masts that support the roof structure. Steel trussed-arches connect the base of the stayed columns along the long directions. Two additional tubular arches reduce the overhang of the roof framing. The PVC fabric membrane roof is suspended from cable trusses and supported by the arch system below. Each roof is supported by two mega stayed columns that rise 72m high and help to anchor the high-tension forces from the 210m long catenary cables holding the fabric membrane. The stayed masts are anchored by means of four 32mm diameter cables. The column core dimensions and weight are optimized by a system of three-tier cross-arms that provide lateral restraint to the 660mm diameter core tube. More examples illustrated the advantages of improving the masts by staying.

David Campbell from Geiger, Lynch, MacBain & Campbell Engineers worried about "Mast Stability and Prevention of Disproportionate Collapse in the Event of Membrane Failure". He stressed the need for the structure to be redundant in order to prevent a local failure from becoming a total collapse. Tension membranes have low tear strength in relation to their tensile strength. This results in the membrane being vulnerable to tear propagation due to imperfections. That is why the ASCE/SEI 55-10 Standard [3] states: "Tension membrane structures shall be designed so that failure of the membrane or of a single supporting element, does not result in progressive collapse of the structure". Masts are elements that require special consideration in the event of a membrane failure as they are often components of considerable size and mass. Issues concerning the stability of masts in post failure modes were reviewed. Various design solutions were shown together with several examples of built mast supported structures illustrating design strategies, philosophies, and solutions (Fig. 22).

A surprising presentation was that of Rami Faraj from de Institute of Fundamental Technological Research, Polish Academy of Sciences. It was about "Development of a new type of inflatable structure – the adaptive rescue cushion". It concerned a special type of inflatable structure, which can be classified





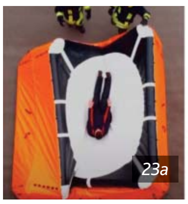


Figure 20. Stayed masts.
Figure 21. HOK Sport, 2003: Algarve Stadium, Faro.
Figure 22a/b. Stage canopy, Barrie.
A redundant cable (nº 12) would hold the masts in the event of failure of the membrane and would create a ridge under snow load to prevent ponding.
Figure 23. Rescue cushion: at work (a), simulation (b).

within the group of airbag systems. An application of airbags is the evacuation of people from heights. In such application airbags are used as so-called rescue cushions, which are operated by fire brigades in case the conventional evacuation is unavailable (Fig. 23). Although relatively high number of patents can be found, the scientific literature in this field is very limited. Nevertheless, importance of the problem and appearing accidents motivated the authors to start the research on development of a new, safer type of rescue cushion system, which will guarantee high performance and adaptive capabilities. A preliminary study revealed the possibility of significant improvements. That is why further research was conducted in order to provide a solution ensuring successful adaptation of the rescue cushion to the evacuation height, as well as the mass of the landing person. The general design methodology and objectives of the optimization have been presented within a case study. Constraints resulting from legal, functional and economic requirements were also discussed indicating the main challenges and directions of further research.

HYBRID AND ADAPTIVE STRUCTURES

Arno Pronk from the Eindhoven University of Technology and being a fan of ice keeps building and experimenting with it. He dealt with: "Fabric formwork with ice in Canada". In his workshop at the University of Alberta, the students tested V shaped beams, little over 6cm thick, made of a mixture of frozen water and paper, reinforced with a pre-stressed foil, fixed on a wooden frame, and smoothed as it froze (Fig. 24). As a result, the reinforced ice resistance can be estimated as three times stronger than the regular frozen water and greatly improving the ductility. The fibre also acts as an insulator and ensures the ice does not melt as fast. The materials are cheap and natural. Therefore, they do not harm the environment.

The lecturer considered the future of building with ice in projects that need to be strong but can be hard to clean up, such as temporary foundations for drilling rigs. He also said that it might have future applications, such as research on Mars, where the environment is very cold. This project with Canadian engineering students might inspire them to new possibilities in cold climates.

Andrey Chesnokov from the Lipetsk State Technical University in: "Adjustment of stresses in the top chord of the dome-like hybrid roof structure" showed the optimization of a hybrid structure described in figure 25. It consists of 8 ridge radial cable beams (1, 2, 3, 5 and 8), 8 valley cables (7). 2 hoop cables (4) and the pre-stressed membrane cladding (6). He distinguished between passive and active strategies to reduce material consumption under various external influences. Passive optimizations could be for example triangulating the top chords for stability enhancement and adding spatial ribs and flexible ties to mitigate bending moments. They are effective (reducing the peak beam stress from 508MPa to 219MPa) but not very efficient because they complicate the structural framework. Instead, the active strategy implies real-time stress adjustments by actuators driven by load cells. In case of sudden external impacts (e.g. earthquake, displacements of supports or soil deformations), the parameters of the construction are dynamically adjusted with jacks embedded in the construction. There is no need to add members or material to the structure to get a similar result. However, this active adaptive concept needs appropriate equipment for controlling the stresses and for implementing the adjustment in real time. It is currently used in solar energy harvesting, dynamic façade modules and damping of vibrations in cable-stayed bridges.

Andrey Chesnokov also presented: "Development and analysis of a pre-stressed cable roof with stiffening girder and polymer membrane cladding". In this case the hybrid structure is another combination of membrane, cables, stiffening girders and struts (Fig. 26). The membrane is attached to the top chord of the cable beams and pre-stressed by valley cables. In order to enhance the efficiency, the girder and the struts are linked together by means of limited design clearances (Fig. 27). The limited clearance is a gap between the girder and the strut that allows the strut to move freely up to a limited value in the vertical direction. In this way overstressing of the girder under uniformly distributed loads is prevented. But under non-uniform impacts, if the clearance run has been consumed, the retainer at the end of the clearance do not preclude levelling the loads and reducing the deformations of the roof. A section of the roof highlighted in figure 26 was analyzed with a computational technique based on static analysis. The polymer membrane cladding was included into the structural model. Deformations of the roof at the pre-stressing and operational stages were provided together with the stiffness properties of the cables and the girder, the required pre-tensioning of the bottom chord and the size of the design clearance. The favourable effect of the girder and the design clearances is remarkable. The deformation of the non-uniformly loaded roof without the girder is 1.45 times as large as the deformation of the roof with the girder installed and skipping the design clearances leads to overstressing the girder by the uniform load.

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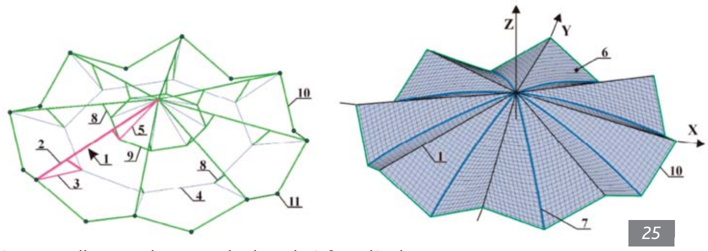
24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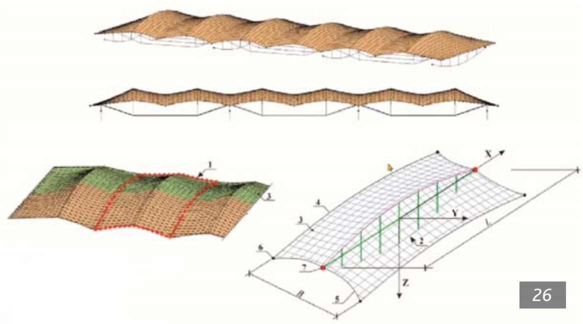
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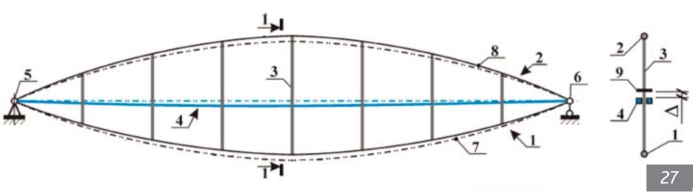
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Figure 24. Alberta students tested V shaped reinforced ice beams.
Figure 25. Hybrid roof structure. Left: framework. Right: membrane
Figure 26. Cable roof structure
Figure 27. Structural model of the roof