Structural experiments with ice (composite) shells

J. Belis
LMO, Ghent University, Ghent, Belgium & Eindhoven University of Technology, Eindhoven, Netherlands

K. Martens, B. Van Lancker
LMO, Ghent University, Ghent, Belgium

A. Pronk
Eindhoven University of Technology, Eindhoven, Netherlands

ABSTRACT: Ice can be a very suitable building material for temporary structures in a freezing environment. When water, mixed with small fibre reinforcements, is sprayed onto an inflatable membrane structure in suitable cold outdoor conditions, a thin shell is formed which increases thickness layer after layer. After deflating the pneumatic supporting structure, it is possible to create a thin-walled, self-supporting ice composite structure. This paper discusses the activities of university students and staff in two recent international projects on the design and construction of full-scale fibre reinforced ice shell structures in Finland. The first structural ice project, completed in January 2015, resulted in the world record of highest ice structure (22 m). The second project is completed in February 2016 and consist of a smaller, although geometrically much more complex shell structure.

1 INTRODUCTION

1.1 *Concept*

Ice can be a very suitable building material for temporary structures in a freezing environment. Traditional construction techniques with ice are to some extent comparable to masonry: large rectangular bricks of frozen water, often sawn from natural ice, are stacked on and next to each other. The resulting structure typically is translucent, but (very) thick-walled, such as traditional igloos.

In contrast, more recently ice structures have been realised making use of completely different concepts, which are shortly introduced below.

1.2 *Japan*

Ice shells, which are curved thin-walled structures made of ice, have been used as temporary winter structures since 1980s in northern Japan with sufficient snow and low temperature (Kokawa et al. 2012). The construction method consisted of blowing snow and spraying water in alternating layers onto a pneumatic spherical formwork, as depicted in Figure 1. The latter consisted of a membrane bag and a reticulated covering rope. As the water and snow is quasi-instantly freezing to the supporting inflatable, a thin shell is formed which increases thickness layer after layer. Finally, the pneumatic supporting structure is deflated and a thin-walled ice structure remains. This way, spherical domes have been constructed with a diameter of up to 20 m (Kokawa et al. 2001).

Figure 1. Application of snow and water on pneumatic formwork to create a spherical dome in Japan (Kokawa et al. 2012).

1.3 *Austria*

Dallinger & Kollegger (2012) reported of an alternative method to create ice shells. The latter makes use of the time-dependent distortion of ice to create individual flat ice segments which are subsequently lifted into their final position by means of a pneumatic lifting device under high pressure. In the winter season of 2010/2011 an ice dome with a base diameter of 10 m and a height of almost 4 m was successfully built with this technique, see Figure 2. However, the wall thickness to span ratio was relatively large compared to the Kokawa domes.

Figure 2. Segmented ice dome in Austria; ice segments during the creeping process (Dallinger & Kollegger 2012).

1.4 *Finland*

Further pushing the limits of the Japanese approach of Kokawa's group, a team of TU Eindhoven has built a spherical dome with a diameter of about 30 m in the winter of 2013/2014 in Finland, see Figure 3.

However, a major difference was the material used for the shell: instead of freezing alternating layers of water and snow, a wood fiber-ice composite material was used. Indeed, in suitable cold outdoor conditions, a mixture of small wood fibres suspended in water was sprayed onto a large inflatable spherical membrane structure with a reticulated covering rope. The main advantage of the wood fibre-ice composite material, also sometimes referred to as "Pykrete", is its increased strength and toughness compared to natural ice (Vasiliev 2003) . However, this material also has disadvantages, such as the brown colour, which is not harmonizing with the surrounding white winter landscape. Furthermore, it was a difficult task to preserve the homogeneity of mixture, where local concentrations of wood fibres could easily cause obstructions in the hoses and pumping installation used.

Based on this successful experiment, two subsequent international projects have been organised by TUe on the same location (Juuka, Finland) in the following winters. From a geometrical point of view, they significantly differ from the spherical domes realised during the previous projects. Two structures are generally presented below.

Figure 3. Spraying of wood fibre-ice composite in Finland, winter of 2013/2014 (photo: B. van Overbeeke, TUe).

2 WOOD FIBRE-ICE COMPOSITE CHURCH

2.1 *Inspiration*

The project constructed in the winter of 2014-2015 was roughly inspired by the Sagrada Familia, the famous church in Barcelona designed by Antoni Gaudí which started construction in 1882. The project in Finland aimed at a simplified geometry, composed of a main tower, four towers near the entrance, and the ship in between. As a scale factor of about 1:5 was applied, the targeted height of the main tower was about 30 m (Pronk et al. 2014, Pronk et al. 2015, Belis et al. 2015). The project was part of the master thesis project of Jordi Kern and Teun Verberne (TU Eindhoven, supervisor A. Pronk) and was strongly supported by an international team of mainly students and staff from Eindhoven University of Technology with assistance from, amongst others, ten students and three staff members of Ghent University.

2.2 *Formwork*

For all of the towers, PVC coated polyethylene fabric was used for the supporting inflatables, covered by an articulated rope net, see Figure 4. The overall appearance of every individual tower was more or less a vertical paraboloid, with a relatively small horizontal cylindrical tube-like element at ground level to connect a pressurising ventilator. An articulated covering rope was provided across the surface of all towers to better control the overall geometry and to introduce a certain surface roughness, in particular on the steep walls of the towers.

As for the ship, a branching cable structure was foreseen to be suspended from main cables between the main tower and the front towers. The branching cables were intended to transform into self-supporting branching columns once they had frozen.

Figure 4. Formwork fabric for the four front towers of the Sagrada Familia project ready to be inflated (Photo: Bart van Overbeeke, TUe).

2.3 *On-site construction*

Similar to the spherical dome erected during the previous winter, the formwork was sprayed with a mixture of sawdust and water, so a wood fibre-ice composite was created. Depending on the weather conditions, snow layers were also formed regularly on the shell, making the layers less homogeneous. This was accepted, although the thickness of the intermediate snow layer was kept below about 1 cm to prevent delamination of the different layers in the composite shell.

The suspension was mixed in an open, unprotected container on the building site from which it was pumped by hoses to the different spraying positions.

The different towers were erected more or less simultaneously, whereas the cables of the ship were positioned in a later phase. The construction schedule was challenged by several occasional events, such as very low temperatures (about -30 °C), causing freezing of pumps and hoses, relatively warm temperatures (-5 °C), making it very difficult for the mixture to freeze timely, in particular on the steep walls of the towers, and power breakdowns, due to which actually the main tower was temporarily deflated and damaged. Consequently, the main tower could not be finished completely in time, so it was decided to suspend the cables for the ship from auxiliary columns. Still, the overall appearance of the structure was very nice, and the world record of highest ice structure was achieved by the entrance towers, which were about 22 m high, see also Figure 5.

Figure 5. Wood fibre-ice composite church, with four front towers, column-suspended branching cables for the ship, and unfinshed main tower, winter 2014/2015 (photo: Bart van Overbeeke, Tue)

3 CELLULOSE-ICE COMPOSITE SHELL

3.1 *Inspiration*

The most recent ice composite structure (winter of 2015-2016) was inspired by the works of Félix Candela, in particular by his reinforced shells built in Xochimilco, Mexico, and Valencia, Spain. Both shells have a very similar geometry, based on eight hypar shells composed in a radial pattern. The diameter of the ice composite shell was chosen to be about 15 m, corresponding to a scale of about 1:3 compared to the original in reinforced concrete. This project was part of the master thesis of Bram Ronsse (UGent, supervisor J. Belis) and was strongly supported by his colleague master students following the “Spatial Structures” course and by the staff of the Laboratory for Research on Structural Models (LMO) at the Department of Structural Engineering of Ghent University (Belis et al. 2016).

3.2 *Formwork*

Although the colour of the membrane was different, again a PVC coated polyethylene fabric was used for the pneumatic mould. However, no rope net was applied here; only four pretensioned ropes were used to articulate the valleys in between the different hypar sectors and to control the overall height, in particular at the central node at mid span. Later during the construction works, additional arch-shaped ropes were provided in each sector from the tops of the cantilevering parts of the roof structure to the basis of the main cables to help defining the final perimeter. Indeed, the geometry of the inflatable was made like a three-dimensional star, the vertices and edges of which needed to be cut afterwards to obtain the desired shape of the pavilion, see Figure 6.

Figure 6. Test inflation of the fabric formwork for the Candela pavilion at Ghent University during the fall of 2015.

3.3 *On-site construction*

Learning from the previous ice project, this time a cellulose-ice composite was used which turned out to be much more homogeneous. The water and cellullose were semi-automatically mixed by two electric motors in an open container, which was now positioned in a closed tent provided with heating to prevent freezing of the installation. No problems occurred with this solution.

Apart from the preparative formfinding, design, numerical analysis and inflatable manufacturing works performed throughout the semester in Ghent, little more than two weeks had been foreseen to construct the whole shell on site. Although this was much more time than what would theoretically have been necessary in ideal conditions, it was tight in reality because of the unfavourable actual weather conditions met. Indeed, after having two days of about -20 °C, the next week average temperatures were only about -4 °C, which was not sufficiently cold to build the shell. The main activity of the student teams then was to constantly remove snow from the structure. During the second week temperatures happily were slightly better, with minimum temperatures of about -9 °C for two days, which allowed to obtain an average wall thickness of no less than 5 cm, which was sufficient for the shell to properly support itself according to the calculations.

Subsequently, the pneumatic formwork was deflated and removed in one piece. Then, the outer vertices and curved edges of the eight individual sectors were cut with a chainsaw to obtain the final geometry (Figures 7 & 8). The four original blue ropes in the valleys of the radial structure were frozen to the ice composite and formed a nice visual articulation of the inner vault edges, as illustrated in Figure 9.

In parallel to the works on the Candela pavilion, material tests were performed on site as a cooperation between Ghent University and the University of Minho to determine the compressive strength of the cellulose-ice composite relative to natural ice (Cruz & Belis 2016).

In addition, a team of Ghent University also performed topographic measurements and photogrammetric analyses of the structure at different stages during the construction (Deruyter et al 2016).

Figure 7. Candela Pavilion after removal of the balloon, before cutting of the edges.

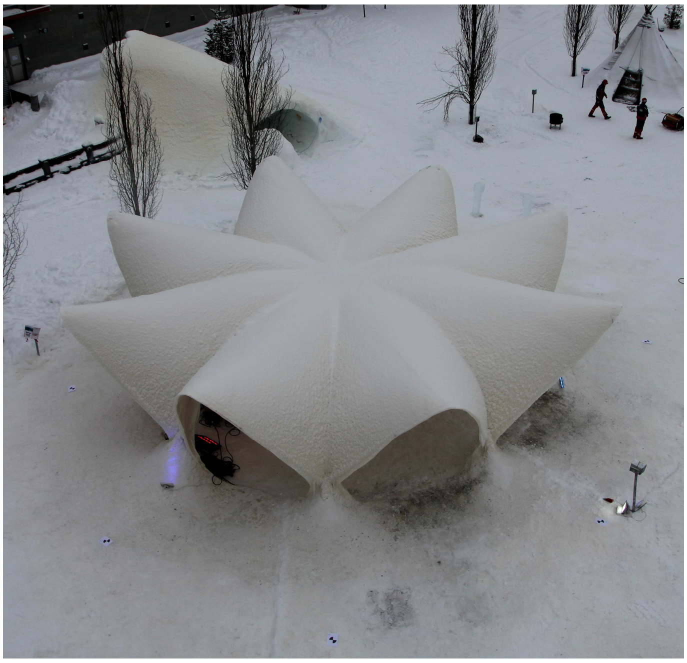

Figure 8. Finished Candela Pavilion, winter 2015/2016.

Figure 9. Interior of the Candela pavilion in cellulose-ice composite with blue articulated ropes used to preload the inflatable formwork.

4 CONCLUSIONS

Several experiments reported in literature have demonstrated that domes can be constructed out of ice or ice-based composite materials in colder regions in the world. In addition, in this paper it is also demonstrated that also shells with a more complex geometry can be constructed with those materials.

Although creep was significant in all of the projects discussed, cellulose-ice composite is a very promising material for such structures due to its relatively high resistance and toughness without aesthetic compromises.

However, a crucial factor for success is the weather, in particular the temperature, which sometimes can be highly unpredictable as illustrated by the cases discussed.

Finally, as ice (composite) structures are typically temporary constructions, they form a very suitable object for innovative building research as well as for educating engineering students and training their problem solving capacities in a "real" building context.

5 ACKNOWLEDGEMENTS

All participating students are acknowledged for their efforts in the design and construction of this project. The Structural Ice Association, the municipality of Juuka, and TU Eindhoven (in particular Teun Verberne, Jordi Kern, Thijs van de Nieuwenhof and Roel Koekkoek) are acknowledged for providing the overall framework and coordination of the Juuka in ice projects. Bram Ronsse (UGent) is acknowledged for his work on the Candela shell project, and Paulo Cruz (University of Minho) for his work regarding the material testing. Greet Deruyter, Hanne Glas and Koos Fransen (UGent) are gratefully acknowledged for their assistance. The company Sioen is acknowledged for assisting in the welding of several parts of the inflatable. Many thanks also for the media team. Finally, all volunteers and local people who assisted somehow in the Juuka in ice project are gratefully acknowledged for their share in this unique experience, with special thanks to Matti Tuominen, Risto Inkinen, Nike Maria Luodes, Heidi Tanskanen and Tuula Ikonen-Graafmans.

6 REFERENCES

Belis, J., Pronk, A., Martens, K., Van Lancker, B. & Dispersyn, J. 2015. Experimental Construction of a Temporary Church in Reinforced Ice, World Congress on Advances in Structural Engineering and Mechanics (ASEM), Incheon. p. 1-7. ISBN 978-89-89693-39-0.

Belis, J., Ronsse, B., Martens, K., Van Lancker, B., Cruz, P.J.S. & Deruyter, G. 2016. Reinforced Ice Structures: in the footsteps of Candela. 3rd International Conference on Structures and Architecture (ICSA), Guimaraes. In press.

Cruz, P.J.S. & Belis, J. 2016. Compressive strength of ice and cellulose-ice composite. 3rd International Conference on Structures and Architecture (ICSA), Guimaraes. In press.

Dallinger, S. & Kollegger, J. (2012). New Construction Method for Ice Domes. *Structural Engineering International*, Volume 22, Number 3, 385-390.

Deruyter, G. …XXX. 2016. Title. 3rd International Conference on Structures and Architecture (ICSA), Guimaraes. In press.

Kokawa, T., Ttoh, O., Watanabe, T. (2001). Re-challenge to 20M span ice dome. Proceedings of IASS. Ed. Kunieda. Nagoya, Japan., TP187. 1-8.

Kokawa, T., Watanabe, K. & Watanabe, T. (2012). Ice shell – Contemporary 'Kamakura' 2nd International Conference, Mukogawa Women's Univ., Nishinomiya, Japan. 70-75.

Pronk, A.D.C., Borgart, A., Hijl, J.M. & Pluijmen, R.M.F. 2014. The calculation and construction of 30 meter span ice dome. IASS-SLTE Symposium, Brasilia.

Pronk, A.D.C., Verberne, T.H.P., Kern, J. & Belis, J. 2015. The calculation and construction of the highest ice dome - the Sagrada Familia in Ice. In: Proceedings of the International Society of Flexible Formwork (ISOFF) Symposium 2015, Amsterdam. 1-13.

Vasiliev, N.K. & Gladkov, M.G. 2003. Ice Composites: Mechanical properties and methods of creation. Port and Ocean Engineering under Artic Conditions, Trondheim, Norway.