The 2015 World Congress on
Advances in Structural Engineering and Mechanics (ASEM15)
Incheon, Korea, August 25-29, 2015

Experimental Construction of a Temporary Church in Reinforced Ice

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ABSTRACT

During the winter of early 2015, a replica of Gaudi's Sagrada Familia was built in ice on a scale of 1:5 in Finland. The international project was jointly prepared and executed by students and staff of TU Eindhoven (NL) and Ghent University (BE). The structure was built in subsequent steps. First, large pneumatic membranes, provided with a reinforcing rope net, were anchored to the ground and inflated. Subsequently, a mix of water and small wood fibres was sprayed onto the inflatables at outdoor temperatures of approximately -20° C, making it to freeze in multiple thin layers until the required structural thickness was reached. Finally, once the ice shell had gained sufficient strength and stability on its own, the supporting membrane was deflated and removed. Although various technical and environmental problems posed severe challenges to the project teams, the world record of highest ice structure was achieved (22 m).

1. INTRODUCTION

Although ice is a brittle material, it has a significant compressive strength which makes it suitable as a construction material – provided that environmental temperatures are well below 0 °C. Probably the best known ice structures are traditional igloos, which typically are more or less spherically shaped and consist of stacked brick-like blocks of ice and/or snow (Pronk & Osinga 2005).

However, more recent ice structures are shells, i.e. doubly curved, thin-walled structures which preferably have a geometry which is optimized for membrane forces (Isler 1986). For example, at Tokai University in Japan, Kokawa and his team have investigated a 20 m dome based on the geometry of a spherical cap (Kokawa et al. 2001, Kokawa & Watanabe 2012). Based on the principles developed by Kokawa et al., in 2014 a 30 m reinforced ice dome was designed and built by the Technical University of Eindhoven (The Netherlands) in Juuka, Finland (Pronk et al. 2014) (see Fig. 1, left). Following the success of the latter project, a new structural ice challenge was proposed: building a replica of Gaudi's Sagrada Familia on a scale of 1:5 (see Fig. 1, right). Due to the rather complex shape of Gaudi's original design, the geometry was simplified to the four front towers, the main tower, the nave, and the entrance. Although the original church is situated in Barcelona, Spain, the ice structure was located in Juuka, Finland, for obvious environmental conditions, during the winter of early 2015.

Fig. 1 Reinforced ice structures by Pronk et al. Left: picture of 30 m span dome, 2014. Right: Rendering of Sagrada Familia in ice, 2015.

In contrast to the previous projects, the Sagrada Familia in ice was developed and constructed by international teams. Apart from TU Eindhoven, which was the leading partner, the project was strongly supported by teams of Ghent University in Belgium, where 40 students in small teams investigated small parts of the project during the winter semester. Subsequently, ten of these students, supported by three UGent staff members, very actively participated in the construction of the temporary ice church in Finland.

2. REINFORCED ICE

Ice composites are known to have interesting properties (Vasiliev & Gladkov 2003, Vasiliev et al. 2011). In this project, Pykrete was used as the main building material for the shells. Pykrete is a mixture of water and wood fibres (sawdust) which is frozen. Its overall strength en toughness exceeds the performance of common ice. An esthetical disadvantage of Pykrete is its brown colour, which is due to the use of timber fibres.

Different groups of students executed tests to check the Pykrete material properties as a function of different parameters, such as fibre percentage (see Fig. 2). It was remarkable that different tests yielded significantly different values, resulting in a large dispersion (e.g. for a mix with 10.5% of fibres the average compressive strength was ranging from 3.74 MPa on prisms to 12.45 MPa on cubic specimens). In addition, non-homogeneity was to be expected also due to gravity and also due to additional layers of snow falling on the partly completed structure. Consequently, large safety factors needed to be taken into account for the structural analysis of the shells.

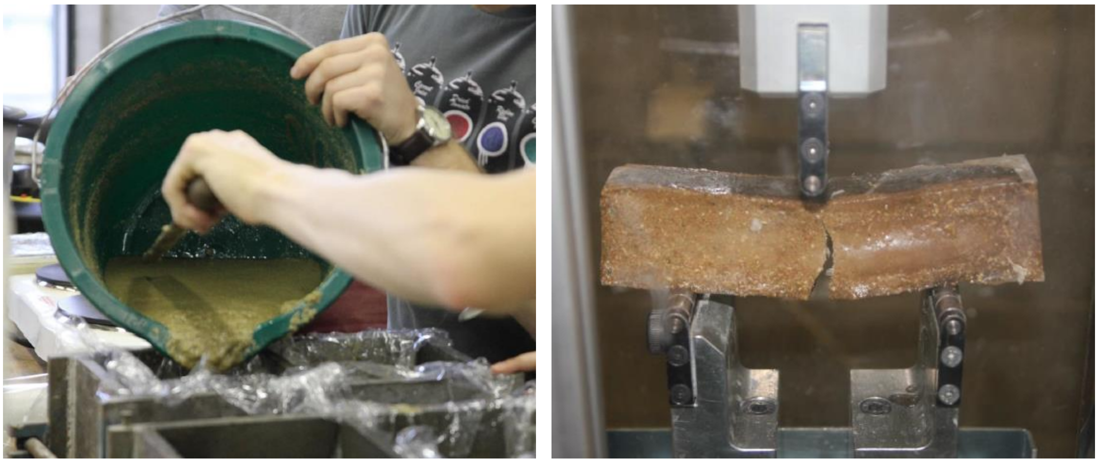

Fig. 2 Material tests by students. Left: sample casting. Right: bending test on Pykrete specimen

3. CONSTRUCTION METHODS

3.1 Inflatable formwork

Inspired by Kokawa's examples, closed inflatable membranes were reinforced by ropes and served as flexible formwork for the later-applied Pykrete. Separate student investigations focused on the optimal way of erecting the balloons (see Fig. 3, left). In particular for the main tower, which was about 30 m high, friction between the expanding balloon and the surrounding rope net turned out to be an issue. Finally, it was decided to suspend the balloon and cable net from a lifting crane, and inflate it only then. This method worked fine for the erection of the towers (see Fig. 3, right).

Fig. 3 Inflatable formwork. Left: Scale model test. Right: about 30 m high main tower (back) and about 22 m high front towers (photo: Bart van Overbeeke, TU/e)

Still, significant wind forces acting on the extremely lightweight balloon caused relatively large displacements which complicated the construction of the ice shell around it and which even endangered the stability of the inflated formwork, in particular for the main tower. Consequently, it was decided to initially limit the inflation of the balloon for the main tower only to its lower half. As this reduced the initial balloon height with about a factor two, stability problems due to wind were effectively overcome. Only in a later phase, when the base of the ice shell had gained sufficient thickness to help stabilizing the upper half, the formwork was inflated up to its full height.

3.2 Applying Pykrete

Subsequently, a mix of water and small wood fibres was sprayed onto the inflatables at outdoor temperatures of approximately -20° C (Fig. 4), making it to freeze in multiple thin layers until the required structural thickness was reached.

Fig. 4 Spraying of Pykrete onto inflated formwork of entrance towers

A schematic representation of the spraying of the reinforced ice is depicted in Fig. 5. Multiple teams in different time shifts relieved each other so that the works were in principle continuously ongoing during 24 hours a day. Finally, once the ice shell had gained sufficient strength and stability on its own, the supporting membranes were deflated and removed.

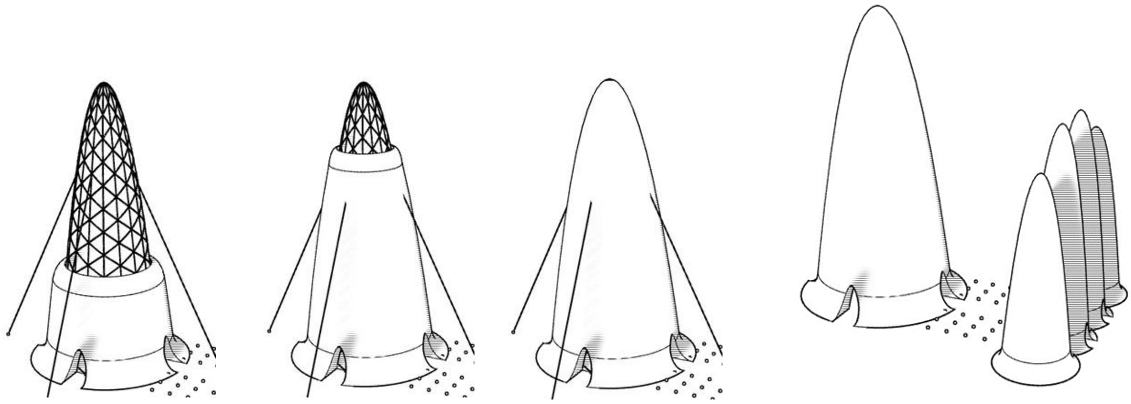

Fig. 5 Schematic representation of applying the Pykrete shell around the inflated formwork of the towers

4. PROBLEMS ENCOUNTERED

As expected, several ad hoc problems complicated the timely construction of the Sagrada Familia in ice.

4.1 Temperature

The optimal operating temperature for instant freezing of sprayed Pykrete is about -20 °C. However, during multiple days the outside temperature was around -5 °C, which is too high to continue the work. Consequently, while waiting for the outside temperature to drop back to normal levels for this season, serious delays were encountered during which the work was completely put on hold.

In contrast, the teams were also confronted with temperatures which were even colder than -20 °C. At about -25 °C, major logistic problems were experienced as pumps and other technical installations were freezing, stopping the normal Pykrete flow.

4.2 Technical issues

Apart from freezing installations, there was also a temporary power breakdown. A major effect of the lack of electricity was that the ventilators shut down which are needed to keep the inflatable formwork under pressure.

4.3 Main tower balloon rupture

Indirectly, and in combination with wind, this caused major damage to the balloon of the partially completed main tower. Indeed, the upper part of the partially deflated balloon was blown over the thin upper rim of the ice shell, breaking down some pieces of it. Indeed, part of the shell around the upper part of the main tower was lost. Subsequently, due to contact with the sharp ice rim, the balloon ruptured and deflated completely. Although this again caused significant delays to the intended time schedule, the balloon was repaired on the spot and inflated again relatively quickly. Still, the main tower could unfortunately not be finished completely.

5. ACHIEVEMENTS AND CONCLUSIONS

Fig. 6 depicts some of the intermediary stages during the construction of the ice structure.

Fig. 6 Construction of the Sagrada Familia in ice – intermediary stages

In spite of the problems and the delays which made it not possible to complete the full structure, the project was a great achievement. The front towers of about 22 m height were completed and currently hold the record of world’s highest ice structure. The international cooperation went very smooth and yielded new friendships across borders. Many young engineers and architects had a unique learning experience by not only designing a real, full-scale structure out of an unusual building material, but also by actually building it. They were constantly challenged to use all their engineering skills to solve a myriad of ad hoc problems during construction. Finally, the structure was officially opened to the public on January 24th, 2015, after which it attracted about 10 000 visitors.

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