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The calculation and construction of the highest ice dome - the Sagrada Familia in Ice

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Abstract
This paper describes the calculation and construction of the Sagrada Familia in Ice realized in January/February 2015 in Finland. The Sagrada Familia in Ice has been built by using the construction method of T. Kokawa and freezing textile fabrics and ropes combined with the relatively unknown material pykrete. The construction method has been analyzed and adjusted to the design of the Sagrada Familia in Ice. The design of the ice dome is based on the original Sagrada Familia by Antoni Gaudi and was a 1/5 scale model of some of the aspects of the original. The design consisted of five domes, the nave and the entrance. The domes were constructed by using an inflatable formwork as a mould on which water, snow and pykrete were alternately sprayed in thin layers to create a pykrete shell. The columns of the nave were constructed by freezing a suspended rope structure by alternately spraying water, snow and pykrete. The roof and the entrance were constructed by freezing textile fabrics using the same spraying technique. The construction process requires a temperature of -8°C or lower.

The construction material pykrete is fiber-reinforced ice which can be 3 times stronger than regular ice. By conducting various experiments the construction method has been analyzed and improved. High quality sawdust is mixed with water and sprayed onto the membrane with a centrifugal pump and an adjustable nozzle.

Keywords: Pykrete, shotcrete, ice composite, ice dome, Sagrada Familia, Gaudi, textile fabrics, shell structure, pneumatic formwork, Heinz Isler, T. Kokawa.
1. Introduction

This paper describes the calculation and construction of the Sagrada Familia in Ice, an ice building based on the design of the original Sagrada Familia, realized in Juuka, Finland in January/February 2015. It gives more insight on the possibilities to reinforce ice with bio-based materials. The goal of this paper is to give a contribution to the search for alternative bio-based construction materials with a low environmental impact.

Since 1985 Tsutomu Kokawa has been building various ice dome structures in collaboration with the Tokai University. In 2001 he constructed an ice dome with a span of 25 meters. The information available from the previous realized ice domes and experimental studies by T. Kokawa have been of great interest in the construction of the ‘Pykrete Dome’ with a span of 30 meters, which has been realized in the winter of 2014 by students of the Eindhoven University of Technology (Pronk et al. [9]). The technique developed by Kokawa has been adjusted and combined with the application of fibre-reinforced ice (pykrete). Since the Second World War, research is conducted on the application of fibre-reinforced ice, an ice composite called “pykrete”, developed by Geoffrey Pyke. Different studies demonstrated that the addition of (natural) fibres to ice structures results in higher strength properties of the ice. For more information about the material properties and development of shot pykrete, please see the IASS 2014 paper by Pronk, Vasiliev, Janssen and Houben. This paper will focus on the application of reinforced ice in the construction and calculation of the Sagrada Familia in Ice.

The Pykrete Dome project used an inflatable mould to create an ice dome with a 30-meter span. This construction method has been developed by T. Kokawa. The pneumatic formwork is created by welding two simple circular patterns together. The formwork is covered by a reticulated rope net to determine the shape of the inflatable. The rope structure takes the heaviest tension, which decreases the requirements of the membrane. The membrane can be reused after the dome is finished, which results in a cheap construction method. During the realization of the Pykrete Dome project several pavilions were successfully constructed by freezing ropes and textile fabrics. The goal of the Sagrada Familia in ice was to investigate the possibilities of combining the building method used to construct the Pykrete Dome together with freezing ropes and textile fabrics.

The design of the Sagrada Familia in Ice is, as the name implies, based on the design of the Sagrada Familia by Gaudi. Ice has relatively poor structural properties and is only suitable when it is under compression. Therefore, the catenary design method used by Gaudi, in order to obtain the ideal shape for his cathedral, fits perfectly when using ice as a construction material.

Figure 1, 2, 3: 1) Pykrete Dome project, 2) Pavilion constructed by freezing suspended ropes, 3) Pavilion constructed by freezing textile fabric
Heinz Isler also used these ‘catenary’ principles in some of his work. In 1961 Isler presented his paper “New shapes for shells” at the first conference of the International Association for Shell and Spatial Structures in Madrid, in which he briefly introduced three non-conventional form-finding methods for shells: 1) the freely shaped hill, 2) the membrane under pressure and 3) the hanging cloth reversed. Isler considered the hanging cloth reversed to be the most satisfactory. Isler created a number of frozen structures using only water and textile fabrics using this technique (Chilton [1]).

The realization of the Sagrada Familia in Ice was completed in a 24/7 process by 4 teams who worked in shifts. The construction process requires a temperature of -8°C or lower. Four of the domes (2 x 21 meters and 2 x 18 meters) and the column structure of the nave were successfully constructed. The biggest dome could only be realized halfway due to unfavourable weather conditions. The entrance and the roof of the nave have never been finished. The realized ice structure was open for public for about three weeks. After the three weeks the temperature rose above 0°C, which initiated the melting process resulting in an unsafe structure. At the end of April the structure was melted that far that it had to be broken down.

2. Reinforced Ice

The positive structural effects of the reinforcement of ice has been known for many years. The inhabitants of northern regions traditionally used lichen to strengthen their igloos (Vasiliev et al. [10]). However, the first scientific studies for the application of ice composites were undertaken in the Second World War by Geoffrey Pyke and his team. After several experiments Geoffrey Pyke learned that a mixture of ice and wood fibres created a strong solid mass, much stronger and ductile than pure ice.

Research conducted by Hijl and Pluijmen [2] showed that a 10% sawdust weight ratio appeared to provide the best values for both mechanical and processing behaviour. This optimized behaviour concerns the homogeneousness, the processability, the toughness and strength of the pykrete. The particles of the sawdust have to be small (up to a maximum of 2 mm). When the sawdust is saturated, it becomes heavier than water and sinks to the bottom. To maintain the homogeneous behaviour of the mixture, the sawdust should be prevented from sinking. When using pumps to process the pykrete mixture and retain the homogeneous aspects, extra attention should be paid to the size and type of the pump. The small particle size (sawdust) creates a better processability. Bigger particles will block a pump immediately.

The compressive strength of pykrete with a 10% sawdust weight ratio can be 12.45 N/mm² and the flexural strength can be 3.74 N/mm². Compared to regular ice (3.18 N/mm² and 1.24 N/mm²) this is 3 times stronger. The ductility of pykrete is even 10 times better than plain ice. With the improved toughness, the pykrete also allows a higher deformation of the structure and reduces crack formations. Pykrete also improves the resistance against thermos-shock that might occur during the building process as a result of the spraying of water on the frozen shell structure (Janssen and Houben [4]).

Indicative research into the effect on the structural properties of ice when incorporating ropes and textile fabrics proved to be very promising. Samples with a single pre-tensioned fabric at the bottom of the sample showed a 50% gain in flexural strength compared to plain ice samples. The same gains were found when ropes where incorporated into beams of ice. Double layered pre-tensioned fabrics showed even higher gains of the flexural strength, but the main finding was that the double-layered samples were able to show large deflection before collapsing. In practice this could result in safer ice structures, because the deflection gives a warning before complete collapse.
3. Spraying Pykrete

Shotcrete was first introduced in Europe by Earl Weber in 1919. It was used to improve the constructions of mining, tunnels and bridges. Since then, architects have used the construction method to create large free form designs. Many studies and research has been conducted to improve the quality and process of the construction method. This has resulted in many different methods for specific occasions. For creating wet shotcrete, water and possible accelerators are added to the original mixture. The complete wet mixture is pumped through the hose under high pressure. At last, air pressure is added at the nozzle in order to spray thin homogeneous layers of shotcrete onto the formwork. The shotcrete method shows potential for application of fiber-reinforced ice.

Research performed by Janssen and Houben in 2013 concluded that the wet shotcrete method is a better building method for the application of ice composites compared to the dry method. The wet method is assumed to be more suitable mainly because the accuracy of the mixture can be controlled more precisely. Unfortunately the wet method as practiced with shotcrete does not work with snow and ice. The compacting of snow in the nozzle of the shotcrete device makes the liquid freeze so that the nozzle will be blocked with ice. Therefore the spraying of the snow, water and sawdust has to be done in layers like the method developed by T. Kokawa. Water and sawdust was mixed in a basin and was successfully sprayed onto an inflatable formwork with a thin layer of snow using a centrifugal pump. In this method the sensitive water/snow/fibre ratio is difficult to control. In the 2014 realized Pykrete Dome it was proved that the wet shotcrete method is applicable. Afterwards samples were taken from the Pykrete Dome. It proved that the samples were inhomogeneous. The conclusion was that the method has to be improved if more challenging structures have to be built.

4. Construction Method

Japanese Professor Tsutomu Kokawa has studied the effects and behaviour of ice shell structures for many years. In 1985 he started his first experiment with the construction of a 5m and 10m ice shell. These relatively small shell structures gave a good impression on the behaviour of the construction material ice and the unique construction method. In 2001 he finished the largest ice shell structure so far with dimensions of 25m internal span and a height of 9.2m. The construction method developed by Kokawa consists of 3 important parts: the foundation ring, the membrane with rope net and the spraying of snow and water.

![Figure 4, 5, 6: 4) 2D Membrane, 5) Foundation ring, 6) Section drawing foundation](image)

Before making the foundation ring, the total construction dimensions are measured. The next step is to level the construction site. After levelling the construction site, a big circle is set out and the wooden foundation panels are placed. All anchoring points are attached to the wooden panels. Then layers of snow and water are added. The inflatable mould has to have a smooth connection between the membrane bag and the upper part of the ice dome. If not, the gap between the inflatable and foundation has to be filled up. After a week the foundation is ready and the inflatable membrane and rope net can be placed. Most of the time a polyester fiber with a PVC coating is used as a membrane.
material but for economical reasons also PE is used. The inflatable consists of 2 plane circles welded to each other. After inflation the rope net is in equilibrium with the inflatable and will form bulges in between the ropes of the net structure. The combination of the bulges and net gives the 3D mold for a ribbed ice shell only the first number of ice layers are fully carried by the inflatable mold. When the ice shell becomes bigger the shell is taking over and at the end the internal pressure can be released and the inflatable can be removed. By adding water and snow to the inflatable formwork, an ice layer is created. The combination of several ice layers creates an ice shell structure. During the construction process, extra attention is necessary to aspects like the thickness of the layers during the process and the application of snow and water. By using a rotary plow machine, milled snow is blown onto the pneumatic formwork. The snow requires a low density, 0.4 to 0.5 g/cm³, to be milled by the machine. Due to the rotary plow, the snow will be sprayed over the membrane with a proper distribution. The dimensions and capacity of the snow plow machines is dependent on the scale of the ice dome. The water will be sprayed on the snow layer with an adjustable nozzle. This nozzle creates a fine mist to distribute the water over the membrane structure. The snow and water will form a layer of ice of less than one cm thick at a time. This process is repeated until the desired thickness of the shell structure is reached. Research of T. Kokawa shows that one cm ice layer has an average construction time of 1.5 hours, with an average air temperature of -10⁰C. When the layer exceeds this limit, the applied water will only mix with the upper snow layer. This way the underlying layer of snow will not be able to mix with the water and creates imperfections in the shell. The last step in the construction process is the deflation and removing the inflatable membrane together with the rope cover. First the opening is cleared from excessive snow and ice. After that, the air blower is turned off to deflate the membrane. For a 25 meter dome, it takes about five hours to deflate. The membrane and rope cover is folded and can be reused to build another ice structure. The interior of the ice shell reveals a rib structure in the same pattern as the rope cover. This rib pattern improves the structural behavior of the shell. The ‘Pykrete Dome’ project used the same method to construct a 30m span dome. The process of spraying is slightly altered in order to incorporate the pykrete material. The water is replaced by a mixture of water and sawdust and is sprayed on the pneumatic formwork using a centrifugal pump. To speed up the process and to be more independent for the climate conditions the foundation system of Kokawa was also replaced by the use of ground anchors.

![Figure 7, 8, 9, 10: 7) Laying out membrane, 8) Creating foundation and inflating membrane, 9) Fully inflated membrane, 10) Application of snow and water (pykrete)](image)

5. Sagrada Familia in Ice

5.1. Concept
The final Sagrada Familia in Ice design is a result of a combination of various studies. The combined studies in the design are Kokawa Ice Shells, Isler Shells, Pykrete, Shotcrete, Pykrete Dome and Gaudi’s Sagrada Familia.
5.1.1. Design
The design of the Sagrada Familia in Ice is, as the name implies, based on the design of the Sagrada Familia by Gaudí. Ice has relatively poor structural properties and is mostly only suitable when subjected to compression. Therefore, the catenary design method used by Gaudí, in order to obtain the ideal shape for his cathedral, fits perfectly when using ice as a construction material.

The implementation of frozen textiles and ropes has also greatly influenced the design of the Sagrada Familia in Ice. The work of Heinz Isler on frozen textiles and the pavilions constructed by him shows the potential of using ropes and textile fabrics as a mould in ice structures. Heinz Isler also showed that ropes and textile fabrics are very suitable for the formfinding of shells and gridshells. To learn more about formfinding the authors have studied and redone these experiments with ice by H. Isler.

5.1.2. Materialization
Experimental research into reinforced-ice has shown that the flexural and compressive strength of the ice can be greatly improved when reinforcement fibres are added. The most well-known reinforced-ice type is called ‘Pykrete’, a mixture of water and sawdust. The latest research into this material resulted in an optimal mixture of a 10% sawdust (weight) ratio. This 10% mixture has been successfully used in the ‘Pykrete Dome’ project. The 10% pykrete mixture will also be used as the main building material of the Sagrada Familia in Ice. Also the effect of application of textile fabrics and ropes into the ice will be investigated by means of experimental research.

5.1.3. Construction Method
T. Kokawa used an inflatable mould together with a reticulated rope cover to construct ice domes. The mould is used to construct an ice shell by spraying thin layers of water onto the mould. Once the shell is self-supportive the inflatable mould can be removed, leaving only an ice-shell structure.

The ‘Pykrete Dome’ project used this same technique. Only the method for creating the foundation was changed to increase the building speed and pykrete was used instead of plain ice.

The Sagrada Familia in Ice will also be constructed by using the method used to construct the Pykrete Dome. The method, based on the wet shotcrete method, used for mixing and spraying of the pykrete mixture developed in the Pykrete Dome project proved to be successful. The same method was used for the Sagrada Familia in Ice project.

5.2. Location
The ‘Sagrada Familia in Ice’ has to be built in a region where it is cold enough to construct an ice structure. Juuka, a small town in North Karelia, Finland, is located in one the coldest regions in Europe with temperatures ranging from -15°C to -30°C in winter. These temperatures are perfect for constructing an ice structure like the Sagrada Familia in Ice. The municipality of Juuka has approximately 5,000 inhabitants and helped us by providing accommodation, services, transportation and construction equipment.

5.3. Design
The design of the Sagrada Familia in Ice is not an exact replica of the Sagrada Familia. The design is based on Gaudi’s design philosophy. Only the most important structural elements are implemented in the design without all the symbolism and ornaments. Although the Sagrada Familia in Ice is not an exact replica of the original, the design of Gaudi’s cathedral can easily be recognized.

The main features of the Sagrada Familia in Ice can be categorized as: 1) towers, 2) nave and 3) entrance.
To come to feasible measurements we reduced the size with a factor of 5.

Figure 11: Design aspects incorporated into the design of the Sagrada Familia in Ice

5.3.1. Towers
In total the design counts five towers: the main tower, which originally represents Christ, and four towers which originally represent 4 of the 12 apostles.
The main tower has a reduced height of 30 meters and an internal span of 11.2 meters. On top of the tower a cross will be placed to finish the cathedrals look.
The remaining four towers together with the main entrance will resemble the ‘Passion façade’ of the original Sagrada Familia.
The four towers will have various heights. The outer towers will have a reduced height of 18 meters and the two inner towers will have a height of 21 meters. All four towers will have an internal span of 4.8 meters.

5.3.2. Nave
The nave of the Sagrada Familia in Ice is based on the tree-like column structure of the original Sagrada Familia. The columns of Gaudi’s cathedral are designed to optimally carry the loads of the entire structure. The design for the nave of the Sagrada Familia in Ice cannot be an exact replica of the original, but should also be designed to be the optimal structure for its own set of loads.
The columns of the nave of the Sagrada Familia in Ice are designed on a grid of 2 meters. The façade towers and the main tower are connected by the nave with a total of five rows of columns. The roof of the nave will be an abstracted version of the original, without the double layered construction. The nave will have a reduced height of approximately 12 meters at its highest point.
5.3.3. Entrance

The ‘Passion façade’ of Gaudí’s original design has been the reference for designing the entrance of the Sagrada Familia in Ice. The ‘Passion façade’ was the only façade finished before the death of Antoni Gaudí and can therefore be considered to be the most authentic façade of the Sagrada Familia. And being the first one that was finished it could also be considered to be the most characteristic. The reduced height of entrance will be approximately 9 meters.

5.3.4. Design overview

Figure 12: Design overview of the Sagrada Familia in Ice
6. Technical Design & Calculations

6.1. Domes

6.1.1. Form-finding shape

The shape of the towers in the original Sagrada Familia are designed by using the catenary principles. The shape of the towers is perfectly formed by the loads they have to bear. In order to find the ideal shape of the domes of the ‘Sagrada Familia in Ice’ the same principle must be applied.

The form-finding of the domes is achieved by using the software ‘Oasys GSA’. The start geometry of the model was a parabola with a height of 30 m and a width of 11.2 m. By applying loads, generated by only the self-weight of the shell, to the model the program is able to form-find the most ideal shape for the applied set of loads. Of course the loads change once the shape changes, so the form-finding process must be continued until equilibrium is found.

Figure 13: Form-finding process in GSA

6.1.2. Calculations & dimensions

The domes can be categorized into three different types: 1) 30m Dome, 2) 21m Domes and 3) 18m Domes. Only the 30m dome will be discussed in this section, because all domes are calculated according to the same principle.

The thickness of the dome has a gradient of 700 mm to 300 mm. The first element layer is 700 mm, the second layer is 600 mm, the third is 500 mm, the fourth is 400 mm and the top part of the dome is 300 mm thick. Around the openings the thickness of the dome is also 700 mm. It must be noted that in practice the ice thickness near the ground surface will increase with a gradient due to the construction method used to construct the domes.
To determine if the thickness of the shell is sufficient, a structural analysis is performed by applying the loads acting on the structure in a GSA model. The loadings that act on the shell structure are: self-weight of domes, self-weight of the cross, snow loading, wind load domes (0° and 90°), wind load cross (0° and 90°) and tension forces caused by the nave.

A unity check is performed to compare the occurring maximum compression, tension and bending stresses to the design values. The occurring stresses are lower than the design values which means that the thickness of the shell is sufficient.

\[
\frac{\sigma_{YM}}{\sigma_{cd, ice}} = \frac{0.3761}{0.76} = 0.48 \leq 1.0
\]

\[
\frac{\sigma_{YM}}{\sigma_{tens, ice}} = \frac{0.1855}{0.47} = 0.39 \leq 1.0
\]

\[
\frac{\sigma_{YM}}{\sigma_{bend, ice}} = \frac{0.1785}{0.48} = 0.37 \leq 1.0
\]

### 6.2. Nave

#### 6.2.1. Design

The columns of the nave of the Sagrada Familia in Ice are designed on a grid of 2 meters. The façade towers and the main tower are connected by the nave with a total of five rows of columns. The roof of the nave will be an abstracted version of the original, without the double-layered construction.

Figure 18 shows how the nave is built up. It is totally based on arches. The outer columns will bear against the domes.
However this model was based on arches, some columns were too long. Buckling has much more influence on longer columns so a new physical model was made using elastic bands in order to reduce the length of the columns. The elastic band model gives an indication of the form-finded design. Some ropes were added to create a structure with shorter beams. Based on the physical elastic band model an Autocad model was made.

6.2.2. Form-finding
The final Autocad model was used to analyze the form-finding process in GSA. By varying force densities for certain ropes or parts and testing impacts of changing force density the final shape was found. Once the design was set, it was loaded with pre-stressed tensile forces to be able to test it on self-weight. Many small design changes have been made to optimize the structure. After changing the support points in a cyclic process the final model was found.

6.2.3. Calculations & dimensions
We assumed that the columns/beams will be tapered from bottom to top, because of the applied building method. The columns will be built up from the bottom, so more ice growth will occur on the lower parts of the columns. Water that is sprayed on the higher parts will flow downwards so water will pile up more in the lower construction, leaving a tapered column.

The measurements of the nave are shown in Figure 22.

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**Figure 18, 19, 20, 21: 18) 2D base geometry, 19) 3D base geometry, 20) Physical model of elastic bands, 21) Form-finded model in GSA**

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**Figure 22: Dimensions and thickness of the nave structure**
7. Conclusion
Based on the previous experiments and experience with the construction of the Pykrete Dome it was possible to build the highest ice dome of 21 meters in the winter of 2015. After having realized this dome, samples have been made to test the material properties on compression. Because it was not possible to drill cylinders out of the Pykrete dome, cubic samples of 90 x 90 x 90 mm were cut out with a chainsaw. The pykrete samples were much stronger and therefore harder to cut out compared to pure ice. The samples were cut at several locations and heights. At each location, five different samples were taken. The samples were much better as the year before but none of them were completely homogenous and each location provided a unique composition of the construction material. The samples were a combination of layers of pykrete, snow and ice. It was clear that pykrete layers within the samples could resist higher forces than regular ice. The ice shattered after high compression, while the pykrete layers remain in shape and slightly deform over time. Because of the problems we have been facing with the variation in material properties we are looking for the spraying of paper pulp instead of sawdust. The first experiments seem to have an improved result and will be tested in a full scale project next winter in Juuka Finland, where we will try to realize the world largest bridge in ice.

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