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The world's first sprayed net hyperboloid ice structure

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Abstract

In the winter of 2018, a team of architects and engineers from the University of Cambridge built the world's first hyperboloid-net ice structure in Harbin, China. A prestressed hemp rope net was sprayed with a cellulose water mix to form a structural sculpture which won the International Ice and Snow Construction Competition to which it was entered. Ice structures have traditionally been constructed from blocks of ice whereas, this project used a variation of Pykrete sprayed onto a flexible formwork. This paper explores areas of ice construction that have been little researched; the spraying of rope nets, difficulties in the construction of ice nodes, and the buckling of struts during construction are discussed. The project proved the viability of sprayed net ice structures and successfully used rope formwork to pretension the ice columns in a design that was both efficient and novel.

Keywords: Hyperboloid, Reinforced Ice, Sprayed net, Structural modelling, Structural analysis

1 Introduction

In October 2018, a team of student engineers and architects from the University of Cambridge started to design a structural sculpture using reinforced ice as the main construction material. This was their first experience of construction in ice. The 5m tall hyperboloid lattice had inclined columns of approximately linearly varying diameter from 150mm at the base to 75mm at the top, and is shown in Figure 1. Two timber hexagons made up the top (5m diameter) and bottom (2.5m diameter) planes. This paper discusses a number of topics related to this project: the architectural concept, ice as a construction material, the structural modelling and analysis (including the construction sequence), and some future prospects are given.

Since 1985, Harbin, a city in North East China, has hosted the Ice and Snow Festival [?]. It is the largest ice and snow sculpture festival in the world covering $600,000m^2$ [?]. The tallest sculptures are now $46m$ high, requiring 10,000 workers [?], $110,000m^3$ of ice and $120,000m^3$ of snow [?].

Initially, the festival participants were Chinese, but in the last decade it has become an international festival and competition, encouraging larger and more decorative sculptures, such as

Figure 1: The team with the finished structure

the palace in Figure 2. The festival is held from the end of December through to February, and attracts 10 - 15 million visitors [?].
In 2017, Harbin Institute of Technology launched the HIT Ice and Snow Festival, and it soon became a hit on local social media. In the winter of 2018-2019, they hosted the International University Ice Sculpture Competition and the International Ice and Snow Innovation Construction Competition. The University of Cambridge were invited to participate in the Innovation Construction Competition. The brief for the competition was to produce a structural sculpture in ice within a 5x5m square with a maximum height of 5m. The authors investigated a series of designs before constructing a hyperboloid ice lattice.

Figure 2: An Ice Palace at the Harbin International Ice and Snow Sculpture Festival 2019

2 History of Ice

Ice has been used in construction for thousands of years. Ice can only be used in environments with sub-zero temperatures and is only temporary. Early Inuits travelled across what is now Alaska, Canada and Greenland, building ice and snow houses for shelter. The igloos were built of

blocks of snow or ice in a circular form and were good at retaining heat and protecting occupants against wind in harsh conditions.
The first ice palace is said to have been constructed in 1740 in Russia, with huge blocks of ice frozen together with water [?]. During the second half of the 19th century ice palaces were used as centrepieces for popular Scandinavian and North American winter festivals. More recently, the ice hotel industry has developed, with countries such as Canada, Norway and Finland offering rooms sculpted from snow and ice.

2.1 The Invention and Development of Pykrete

During World War II, Geoffrey Pyke developed Pykrete as an alternative to ice, which was up to three times as strong, as well as more durable, flexible, and slower to melt. Pykrete is a frozen composite material, consisting of ice and a form of wood pulp, such as sawdust or paper. The original composition was 14% sawdust by weight [?]. Pykrete was introduced in 1943 as an alternative for ice in the construction of an aircraft carrier (Project Habakkuk) [?]. Whilst scale models were built, the project was never put into action due to the models experiencing buckling and warping.
Subsequent research has been undertaken into Pykrete composition, its uses and potential benefits over ice. Nixon and Smith (1987) researched the fracture toughness of ice composites containing various proportions of newspaper, wood pulp, sawdust or blotting paper [?]. The values of K_{IC} obtained ranged from 5 to 20 times the values obtained for freshwater ice [?]. Houben and Janssen (2013) researched fibre reinforced ice structure, testing the compressive strength of cylinders and beams with varying concentrations of wood pulp [?]. The material properties given in this thesis were used in the analysis of the hyperboloid lattice constructed. One issue still to be solved is the creep experienced during the lifetime of a Pykrete or ice structure. However, as ice structures are temporary, creep can sometimes be neglected.

2.2 Ice as a Structural Material

Ice is often used in construction in the form of blocks due to its high compressive strength and limited tensile strength. Ice can be used as a substitute for unreinforced concrete, or masonry blocks. Igloos and the first ice palaces were built using blocks of ice, usually harvested from local rivers or lakes. The Harbin International Ice and Snow Festival usually uses ice blocks to create its attractions, as seen in Figure 2.
Ice hotel constructors spray special 'wet snow' onto steel moulds, allowing the snow to freeze before removing the moulds. These structures experience an increase in strength as the snow melts and refreezes over time (on a day/night cycle) [?]. Pykrete was sprayed in 2015 by the students of Eindhoven University of Technology over an inflatable to form a thin walled dome [?]. Both forms of construction rely purely on the compressive strength of ice.

2.3 Ice for Spraying

The composition of the ice composite used to construct the net hyperboloid structure was initially chosen to be 2% cellulose paper by weight. If the mixture is too watery, it is not viscous enough to stay on the structure until it freezes. However, the cellulose composition was reduced to 0.6% due to clogging of the nozzles during spraying. When the authors changed the proportion of cellulose paper to 0.3%, the mix became too watery and the structural layers did not build up as quickly.

The mixture was sprayed as fine mist which built up the layers of ice. Direct spraying caused the water mixture to run down the structure, causing ice to build up predominantly towards the base of the structure, and an increase in the size of the icicles. A large volume of waste water was sprayed on the ground and over the ice blocks.

3 Design

A sprayed net design was quickly decided upon due to its aesthetics and because few structures of this type have ever been constructed, giving scope for research and development. The main desire was to have a purely tensile structure during construction which transformed into a purely compressive structure upon release. The authors studied examples of how this could be achieved such as tree structures with top tension rings. This idea developed to become a hyperboloid lattice with tension rings at the top and bottom. The hyperboloid is an inherently stable shape due to the double curvature and has been used widely by engineers including Antoni Gaudi and Félix Candela [**?**]. The most well known hyperboloid structures are cooling towers [**?**].

A compression-only structure was desirable due to the limited tensile capacity of ice (over 3 times stronger in compression). This is why many progressive ice structures are shell structures [**?**]. However, these require inflatable moulds onto which water is sprayed, or tensioned fabric formwork. Both of these are expensive to produce as they must be made uniquely for each structure. In comparison, the rope net is easy to produce in a few hours from materials commonly found in any hardware store.

The beauty of this design was how the formwork became part of the final structure. Ice construction is usually difficult because the formwork required is large and technically challenging as it must hold the water while it freezes (and expands). Through the use of a net, the formwork was easy to design, cheap to produce, and very sustainable. The formwork helped prestress the ice, increasing the overall stability of the structure.

Very few forms allow a tension-only lattice to form a compression-only structure upon release of the loading mechanism. The hyperboloid lattice did this well. At the same time, the structural form was elegant and efficient; as a compression only structure, it had a short load path so transferred the loads applied to it efficiently to the ice foundations.

The authors have seen very few sprayed net ice structures and no papers on this topic. The success of this project demonstrates that this method of construction is feasible for future projects. 3D printing techniques such as that performed by A. Pronk [**?**] are becoming more popular due to the ability to build ice structures without the need for complicated and expensive formwork. However, this requires a printer which has a large upfront cost associated with it. In contrast, the sprayed net technique forms similar structures at a lower cost. One downside of the sprayed net technique, compared to the 3D printing, is that a lot of the sprayed cellulose water mix misses the lattice net and is wasted.

4 Architecture

Situated in front of the university main building, the project aimed to inspire curiosity whilst not competing with the grand architectural backdrop, as shown in Figure 3. Taking the form and meaning of a tree, the self-supporting ice structure stood slightly higher than the surrounding tree-line. At 5m tall and 5m wide at the top, it tapered toward the base (2.5m wide), providing a sense of space with a minimal foot-print; serving as a node for congregation, a place to meet others, for members of the university and public alike. The project balanced its potential imposingness through use of a hyperboloid net structure, in reference to the Shukhov Tower [?]; it minimizes its surface area while maximizing the number of sightlines running through, rendering it more relatable to the human-scale and more reverent to the surroundings. Visitors could also observe icicles on the structure, as seen in Figure 3; an architectural detail that reveals its unique spray-construction process which simulates nature.

Figure 3: The surrounding architecture and icicles

5 Structural Analysis

Finite Element Analysis (FEA) was performed with a range of ice diameters which varied linearly from the base to the top. This was most useful when onsite as it allowed the authors to focus spraying either the top or bottom section of the structure so as to make the sculpture as structurally sound as possible. The buckling modes of Shukhov towers and hyperbolic lattices are well understood and this aided the authors in calculating the buckling loads [?]. Due to the surprisingly warm weather during construction, the desired ice thickness was not achieved. However, the authors still produced a stable structure.

The original design employed a diamond lattice but the structure built included horizontal hoops between nodes. Small scale models of the diamond lattice structure were made from cardboard and wet string, loaded with weights, and then placed in liquid nitrogen. These experiments were successful and showed that even thin columned hyperboloid lattices could support a large enough load before failure. The model demonstrated the overall stability of the design and allowed for rapid analysis of a range of different geometries. As the weather during construction was warmer than expected, the ice did not grow as quickly as desired. Therefore, horizontal hoops were added to increase the buckling load. The addition of hoops was a major alteration to the design form, considering the aim of using a slender form was to challenge the perception of ice being "chunky".

The FEA clearly showed that the deflection of the structure decreased with the addition of the horizontal hoops. The factor of safety against the buckling of the structure was of the order of 5.0 without the hoops and 6.5 with the hoops. The slanting struts of the upper part of the structure were the weakest part, regardless of the addition of the hoops, as they have the longest length and smallest cross-section. Therefore, the addition of the hoops only increased the overall stability of the structure slightly. The buckling of the structure dominated the design as the compressive strength of ice is of the order of $3N/mm^2$ and the stress in the ice was of the order of $0.13N/mm^2$.

6 Construction

Two timber hexagons were fabricated for the top and bottom sections and the corners strengthened using plywood. The hemp rope formwork was then constructed by tying figure of eight knots through holes drilled in the plywood. A grid of timber members was fabricated to rest atop the bottom hexagonal frame near the nodes. Three blocks of ice cut from the river, each with a mass of roughly 600 kg, were then placed atop this grid using a forklift to form the ballast. A chainsaw was used to shape the ice blocks to avoid interaction with the ropes.

The top hexagonal frame was lifted using a mobile crane. Crane ropes were attached to each corner of the hexagon before being lifted. Special care was taken to ensure each rope had a similar tension. This was done by pushing the ropes and feeling how taught they were. A total of 1 tonne of load was applied by the crane. When the crane hook was lowered after spraying, this load became a prestress in the ice columns on the order of $0.14N/mm^2$. This prevented the ice from cracking and allowed the column to utilize more of its compressive strength. The prestress also reduced the amount of sag caused by the weight of the rope and water during the spraying process. Therefore, the column would be straighter and deform less under loading.

The ropes were wetted with water using a garden spray bottle. The ropes were then wrapped in toilet roll before spraying commenced. Initial water absorption, allowing the formation of the infant strut, was aided by the wetted toilet paper and the use of hemp ropes, whose natural fibres made them ideal for this purpose. The natural fibres in hemp also allowed a strong bond between the ice and rope to form, preventing pull-out and maintaining the compressive prestress applied.

Where the ropes crossed, they were tied together using cable ties to increase the strength of the node. If the ropes did not touch, the lines of action would be further apart and could cause strength problems at the nodes.

The structure was sprayed continuously over a period of three days, as seen in Figure 4. Each spray lasted ninety seconds and occurred every ten minutes. This was to allow the water to freeze between spray cycles. The water was sprayed using fireman's equipment with an adjustable nozzle at approximately 0.2 l/s. The nozzle required regular cleaning to avoid the build up of cellulose. The structure was sprayed from different angles to avoid build up of ice on only one side of the rope.

A mixture with a much larger cellulose content was used to reinforce the nodes of the structure, which were not achieving sufficient thickness through spraying alone. The horizontal hoops restricted water flow to the bottom of the nodes, hence they were much thinner than desired. The thicker mixture had paste-like qualities and could be easily placed by hand onto areas which needed to be thicker. A cherry picker was used to access parts of the structure which could not be reached from the ground.

To release the structure, the crane hook was lowered by 50mm to remove the load from the crane straps. The straps had frozen so two workers used the cherry picker to remove the ice from them before disconnecting the structure from the crane. The cherry picker was also used to remove any icicles which were considered too large and were causing safety concerns.

Figure 4: Spraying of the structure throughout the night

7 Future Developments

One technical constraint with the construction approach taken was the uneven distribution of strut thicknesses. It was difficult to achieve uniform thickness whilst spraying without a substantial increase in economic costs, for example, spraying at heights using a cherry picker. Furthermore, it was estimated that as much as 90% of spray mix ended up missing the structure, contributing to a higher material cost. A possible improved construction method to address both issues could be adopting a two-stage approach. For example, using moulding or compaction to achieve an acceptable thickness before proceeding to spraying.

A major limitation encountered in performing safety checks was the inaccuracy in the modelling assumptions. During construction, it was observed that the spray does not adhere to the joints as well as they adhere to the struts. Thus, it was inaccurate to model the structure as a uniformly brittle material as the joints would not have acquired sufficient strength. The structure's behaviour when the ice thickness was insufficient to provide a brittle property was not modelled. Should an ice net structure be constructed in the future, the observations from this project concluded that a better model taking care of the varying behaviour of the nodes and struts should be developed. For example, the structure should be checked in 3 separate stages, namely plain ropes, intermediate and fully coated, where its behaviours could drastically differ. The optimal water-to-cellulose ratio was determined on site via trial and error, which resulted in some delay in the spraying process. Using the observations from this project, the authors agreed that the spray mix formula should be decided in the design stage should another similar project commence in the future. Not only would this save construction time, it would also facilitate better modelling of the structural behaviour if the exact composition of the ice is known. The possibility of using enhancing additives, for example, thickening agents like guar gum and xanthan gum, should also be explored in future projects. It was important to find a fluid of the correct viscosity; too viscous and it would clog the nozzle and too watery and the mixture would run off the surface before freezing. Furthermore, creep is a major consideration in ice structural design. No creep analysis was performed throughout the design process due to time limitations. However, it is important that this is researched further. The creep behaviour of the ice should be tested in a laboratory, including the effects of the unusual construction technique.

8 Conclusion

The authors of this paper successfully designed and constructed the world's first hyperboloid lattice ice structure in Harbin, China, using an innovative sprayed net technique. The properties of ice encouraged the use of a form that produced a purely tensile structure during construction and transformed into a purely compressive structure upon release. By prestressing the net, the imperfections associated with the ice struts were reduced and a prestress was applied to the ice struts. Hemp rope was used throughout to improve the bonding with the ice. A water and cellulose mixture was used to spray the structure as it was both stronger and less viscous than conventional ice. Most ice structures require large, complex formwork whereas this construction technique was cheap, sustainable and fast.

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