3D printed grid shell in ice composite

Proceedings of the IASS Annual Symposium 2019 – Structural Membranes 2019
Form and Force
7 – 10 October 2019, Barcelona, Spain
C. Lázaro, K.-U. Bletzinger, E. Oñate (eds.)

3D printed grid shell in ice composite

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Abstract

This paper presents the design of a grid shell that is made of fibre reinforced ice and constructed by combining additive manufacturing with an inflatable mould. While previous fibre reinforced ice structures were constructed by spraying, additive manufacturing with ice has not yet been tested before. Additive manufacturing is a stepwise production technique where material is being added layer by layer, resulting in a high degree of formability. Combining this printing technique with sustainable materials such as ice makes it possible to develop more sustainable structures and building applications in cold environments such as Mars or the poles. To test this application, a grid shell of fibre reinforced ice was designed and eventually constructed. The grid shell was designed by considering the design constraints of the inflatable mould that needed to support the wet ice layers during construction. The structural capacity of the grid shell was enhanced by performing an optimization procedure on the gridlines. In the end, a theoretical failure load calculation shows that the middle part of the structure could carry more than 6000 kg of additional load. To test this finding, the constructed grid shell was loaded on site with approximately 3000 kg, without showing any signs of failure. By designing and testing this innovative object, this project illustrates that additive manufacturing can successfully be applied for other structural applications such as sculptures, moulding and Mars missions.

Keywords: fibre reinforced ice, additive manufacturing, grid shell, optimization, inflatable formwork.

1. Introduction

The current research into using ice and ice composites for construction is part of a larger movement to investigate new sustainable building materials. Ice and water are widely available, cheap, fully circular without producing waste, and they produce little to no CO2 emissions during processing.

In the past centuries, architects and engineers have explored many possibilities to apply ice for building structures. The first well-known examples of ice-based structural objects are igloos. More impressive structures constructed of ice blocks have been around since 1739, when the first ice palace was built in Sint-Petersburg [1]. In 1942, Geoffrey Pyke started to use an ice composite that existed of water mixed with wood fibres [2]. This mixture formed a strong solid mass, much stronger than pure ice. Inspired by the report of Pyke, Max Perutz investigated the properties of ice composites from sawdust and ice and tested, amongst others, the resistance of pykrete against shock loading and creep mechanisms in ice [3]. Later, during the 1980s and 1990s, Tsutomu Kokawa successfully developed a method to spray “snice”, a special wet and easily processable snow, on moulds to construct igloos with a large span [2].

More recently, an ice research group at Eindhoven University of Technology (TU/e), guided by Arno Pronk, combined ice composites with the spraying method developed by Kokawa [4]. Pronk showed that spraying ice composites increases the composites' strength and resistance to impact and shock-loading. This research showed that a relatively small amount of fibres was required to significantly improve the mechanical properties of ice. In a further research stadium, Pronk replaced the wood fibres in the mixture by cellulose fibres, which have the same impact on the properties of ice [1].

To test his findings, Pronk guided TU/e students in cooperation with other groups to build a number of structures. In 2014, by using these mixtures, the largest igloo dome structure with a span of 30m was realized [4]. In 2016, an attempt was made to construct an ice bridge with a free span of 35 meters [5]. In 2018, the Flamenco tower claimed the position as largest ice tower ever built with a height of 30.5 m [6]. All three structures used an inflatable mould as formwork. The aforementioned achievements show that engineers and design teams are able to successfully realize ice-based (shell) structures with different mixtures and different shapes. Following the success of these building projects, Pronk wanted to further investigate how the processes of 3D printing of ice on an inflatable mould could also be applied in structural applications.

The focus of this paper shifts away from spraying ice composites towards investigating possibilities of 3D printing of ice composites. The reason for this is that 3D printing is a building method that can be used to sustainably print a mould, 3D habitat, sculpture or temporary foundation of ice in cold environments, such as Mars or the poles. To specifically test 3D printing of ice for this project, a grid shell in ice was designed by using an inflatable formwork as supporting structure. Consequently, this project included optimization of the morphology of the grid and the construction and testing of the grid shell structure in Harbin (China).

2. Cellulose reinforced ice

The design group applied a manual extrusion technique, similar to 3D printing, to create a grid shell structure in ice. In order to increase the extrudability, 1.5 grams of Guar Gum and 1.5 grams of Xanthan Gum per litre of water were added to a mixture of water with 8% cellulose fibres. Relevant mechanical data for this composite were derived from experiments by another group of students from the TU/e. Their results are presented in a separate paper [7], but their main outcomes are summarized in Table 1. The cellulose-reinforced ice composite shows plastic behaviour in compression and brittle behaviour in tension, due to which the safety factor for tension was taken somewhat higher compared to the safety factor for compression.

Table 1: Mechanical properties of the used composite

Property	Characteristic value [N/mm^2]	Design value [N/mm^2]
Compressive strength	4.6	1.0
Bending (tensile) strength	3.0	0.3
Modulus of elasticity	550	550

3. Behaviour of shell structures

To analyse the relation between the shape and the mechanical behaviour of a shell, the 'Rain flow analysis' was considered [8]. In this analysis, the behaviour of forces in a shell is compared to the behaviour of water particles that flow along the surface of the shell. From the analysis, it can be stated that the distribution of forces in shells is poor when the applied loading is perpendicular to the surface, and that forces should preferably be guided towards the supports without abrupt changes. Namely, abrupt changes in force direction will obtain bending moments in the edges of the shell. Furthermore, this analysis in combination with theories from other literature resulted in three additional conclusions on the behaviour of shell structures. Firstly, it can be concluded that a double curved shell has a more equal force distribution compared to a single curved shell [9]. Secondly, the combination of upward and inward curvature increases the strength and stiffness of the shell [10]. Finally, inward curvature of the supports increases the buckling load of the shell structure [10].

4. Parametric design and optimization

In order to create a 3D shape by means of additive manufacturing, a supporting structure is needed to prevent the unfinished grid shell structure from collapsing. An inflatable formwork for temporary support of the grid shell is considered to be effective, reusable, and easy to install and dismantle. Due to the internal pressure, inflatables have a circular shape in at least one cross sectional direction. Therefore, the shape of the inflatable differs from the structurally most favourable shape of a grid shell. A comparison was made between the shape of an inflatable and the shape of a structurally optimized grid-shell. This comparison led to the design of a mould with a double curved surface with three openings and inward curved supports. Subsequently, four different grid patterns were designed on this mould with Rhinoceros and Grasshopper, as shown in Figure 1. The principles behind these grids are summarized in Table 2.

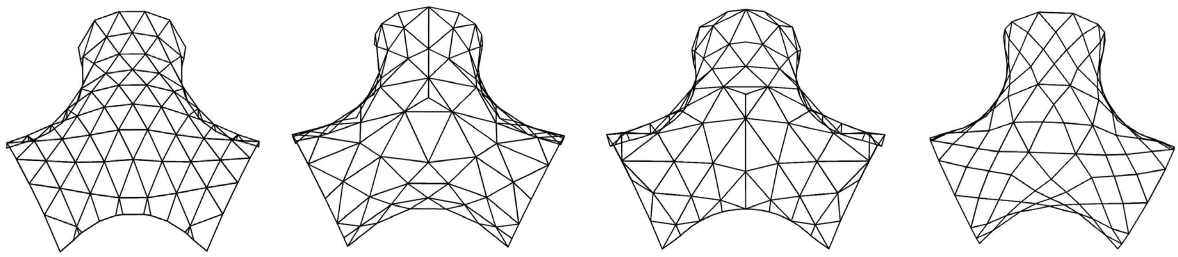


Figure 1: The different grid options that were analysed (from left to right: grid option 1, 2, 3, & 4)

Table 2: Overview of the design principles of the different grid options

Grid option 1: Projection of a triangular mesh on the shell shape	
Advantages: The grid consists of straight, continuous lines on the shell shape.	Disadvantages: The density of the grid at the bottom of the shell shape is lower compared the top, which does not correspond to the expected stress distribution in which higher stresses are expected at the bottom of the shell shape. Furthermore, the grid lines are irregular at the bottom due to the projected grid lines being cut off at ground level.
Grid option 2: Morphology based on strictly horizontal lines and triangles in-between	
Advantages: The grid is denser near the bottom and less dense near the top of the shell, as expected from the stress distribution.	Disadvantages: Direct force transfer to the foundation is prevented due to the presence of kinks in the lines that run from the top of the shell towards the bottom.
Grid option 3: Morphology based on direct force transfer from the top of the shell to the foundation by means of vertically oriented grid lines and triangles in-between	
Advantages:	Disadvantages:

The vertical grid lines allow for direct force transfer from the top to the bottom.	There is some discontinuity of the grid pattern near the openings of the grid shell. In addition, the limited variation in grid density does not correspond with the real stress distribution of the shell.
Grid option 4: Morphology based on continuous lines that are drawn over the solid shell-shape to create a pattern of mainly rhombuses and some triangles	
Advantages: The grid lines are continuous and smooth and they follow the shape of the shell. In addition, the grid density is representing the expected magnitude of stresses, since a denser grid occurs at the bottom compared to the top of the grid shell.	Disadvantages: Rhombic shapes are not stable by themselves, unless the members have a rigid connection in the nodes. As a result, applying rhombic shapes is expected to cause forces, other than compression forces, such as bending moments and shear forces.

The four grid options were analysed by means of FEM analyses and the results were compared. Grid option 3 showed the best results from a structural point of view, since this grid resulted in the least axial stresses under self-weight loading and an equal stress distribution throughout the structure. However, besides a poor architectural appearance, the construction of this grid was expected to be difficult due to the discontinuities that are present near the edges. As a result, the choice was made to optimize a more fragile and open grid (option 4), rather than choosing the structurally best performing grid (option 3). Grid option 4 was subjected to optimization steps that ensured stresses to remain within the limits. This optimization process existed of the subsequent addition of members, while the effect of these additions was monitored. The members that were added in the different steps of the grid optimization process are shown in Figure 2. The outcomes of the optimization analysis showed that the members added in analyses 2 and 3 were the most influential in reducing the deformations and internal stresses in the grid shell. Overall, the optimization of the grid shell resulted in a reduction in deformations of 52%, a reduction in tensile stresses of 56% and a reduction in compressive stresses of 33%. The final design consisted of a grid shell with a pattern that combines quadrilaterals and triangles.

5. Numerical calculations

5.1. Self-weight calculation

After the structure was optimized in shape, size and morphology, a self-weight calculation was performed to verify whether the structure was able to resist its own weight. A density of 980 kg/m3 was used to calculate an ice mixture that consists of 8% cellulose, 0.15% Guar Gum and 0.15% Xanthan Gum. The cross-sectional diameters of the members were 120 mm for the bottom part, 90 mm for the middle part, and 60 mm for the top part. A representation of the structure with the different cross-sections is visualized in Figure 3 with white, green and red struts, respectively.

A self-weight calculation without external loads was assumed to be a sufficiently accurate structural verification due to the openness and small size of the structure (4.0 x 4.0 x 1.8 meter). For the material properties of the ice mixture, a Poisson ratio of 0.15 and a Young’s modulus of 550 MPa were used. The internal nodes were modelled as rigid connections, while the nodes at the bottom were hinged connected to the subsurface. The outcome of this self-weight analysis showed that the maximum compression stress was 0.103 MPa and maximum tensile stress was 0.085 MPa, which are both less than the design limits of 1.0 and 0.3 MPa respectively.

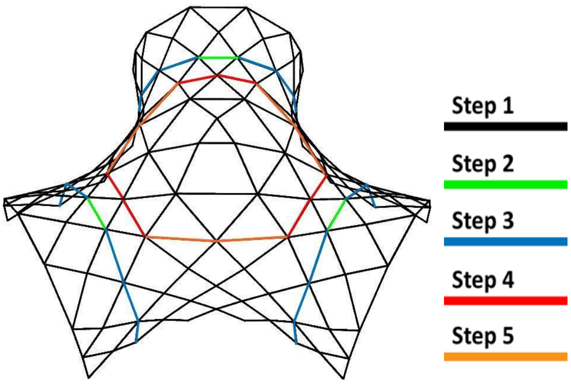


Figure 2: Overview of the members that were being added in the optimization process

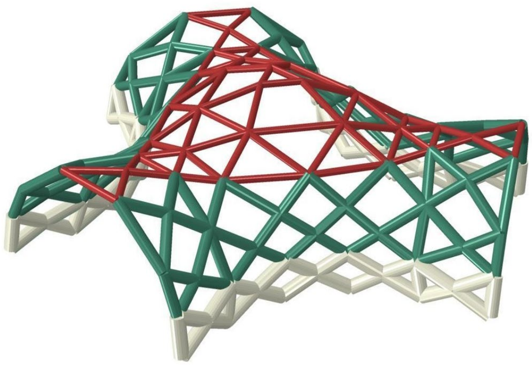


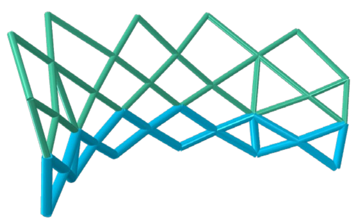
Figure 3: Final grid shell showing the division of the different cross-sections used for the analysis

5.2. Grid shell under construction

During the construction of the grid shell, an inflatable formwork covered by a rope net was used to support the unfrozen ice layers. A numerical study was conducted to investigate the structural behaviour of the grid shell under construction in three steps.

First, the pressure of the inflatable (200 Pa) was modelled as a series of point loads acting perpendicular to the surfaces of the inflatable, which were represented by the grid of the rope net. Assuming an effective width of 100 mm of inflatable pushing against the ropes resulted in a line load of 20 N/m for the ropes. Because large deformations of the rope net were expected, a nonlinear calculation was performed to obtain reliable output. In the second step, the average deformations of the rope net (0.1067 m) and the applied pressure (2 N per node) were used to calculate a fictitious spring stiffness representing the supporting inflatable. This spring stiffness turned out to have a value of 18.75 N/m. In the last step, part of the grid shell under construction was modelled, with the spring supports at the ends and at mid-span of each strut. The struts do not have their final thickness during the construction stage, thus their sections are reduced to 60 mm for the bottom elements and 30 mm for the middle part of the structure. Table 3 shows that the spring supports, representing the inflatable, have a small effect on the stresses and deformations in the grid shell under construction. The stresses seem to decrease slightly as a result of the springs being present. Although both maximum compression and tensile stress are not exceeded for the calculation without springs, the inflatable will still be required as a formwork to support the wet ice mixture during the printing process.

Table 3: Results from the structural analysis for a part of the structure with and without spring supports

Mechanical scheme (cross-sections)		With springs	Without springs	Design value
	Max. tensile stress [MPa]	0.275	0.284	0.300
	Max. compressive stress [MPa]	-0.277	-0.285	-1.000
	Deformation [mm]	5.15	5.40	n/a

5.3. Failure analysis

Lastly, a failure analysis was performed to find the theoretical failure load of the grid shell structure. In this analysis, 21 point loads were added at the top part of the structure. The loads were only applied on the nodes to prevent a situation in which premature (bending) failure of the bars was governing. All point loads were gradually increased in magnitude until the stress exceeded the characteristic compression (-4.6 MPa) or tensile stress (3.0 MPa) for cellulose-reinforced ice. Figure 4 shows that the structure failed in compression when applying point loads with a value of 2900 N per node, which corresponds with a total mass of approximately 6000 kg on the grid shell structure. A possible reason for failure of the reinforced ice structure in compression rather than in tension is that a shell structure is by nature a compression-based structure, due to its curved shape. Consequently, the magnitude of the compression forces in the grid shell is higher than the magnitudes of the tensile forces. Furthermore, an accumulation of compression in the critical nodes where failure occurs can probably be explained by the connection between elements with different cross-sectional diameters. The bars at the bottom part of the structure have a larger diameter and can therefore provide more stiffness compared to the upper part. This discontinuity seems to lead to an increased stress in the less stiff part, which might be the reason for failure.

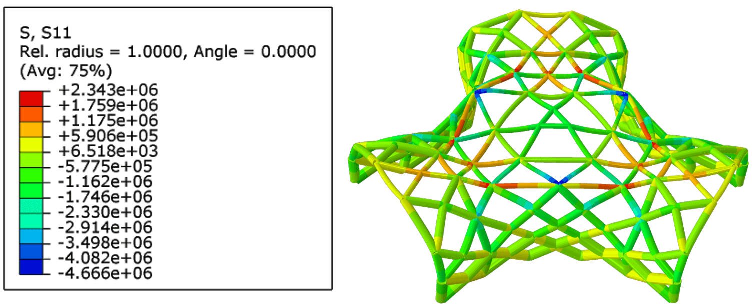


Figure 4: Axial stress distribution [Pa] in the grid shell in the deformed state when a load of 2900 N/node is applied

6. Construction of the grid shell

Several printing methods were tested to find the best printing technique. The tested methods include manual extrusion with piping bags, extrusion with a barrel with overpressure and extrusion with a worm pump. On the short term, the first method appeared to be the most simple and reliable. However, future projects should target the automatization and improvement of the printing process.

To ensure the suitability of the printing process, a test was performed in a cooling cell in Venlo (the Netherlands). From the experiences in this cooling cell, it was concluded that the rope net that held the inflatable mould in place was also a crucial element to allow printing the ice mixture on nearly vertical surfaces. Furthermore, the printing process seemed to be more efficient when the water-cellulose mixture was close to its freezing point at the moment of extrusion, because then the printed material would cure sooner. This way, the curing of the ice composite takes about one hour. The rope net was used as guideline for the printing process as well as for fastening and shaping the inflatable formwork. The net was knotted according to the grid geometry, as exerted from the digital model. The inflatable formwork was 10% oversized and constructed from flat cutting patterns that were welded together. The patterns were made from a PVC coated membrane with polyester fibres.

The final grid shell was built in Harbin (China). To speed up the overall building time, the construction of the grid shell was done in a 24/7 continuous process, starting from the foundation going upwards to the top. By the time that all gridlines had the required structural thickness, LED-lights were attached to the structure, and the supporting inflatable and the scaffolding were removed. Afterwards, the appearance of both the grid lines and the foundation plate were improved by applying the printing techniques at specific locations that needed smoothening. The final result of the construction process is shown in Figure 5. On January 6th, the structure was tested with a load of approximately 2500-3000 kg. Because the load was lower than the theoretical failure load of 6000 kg, the structure did not fail, as predicted.

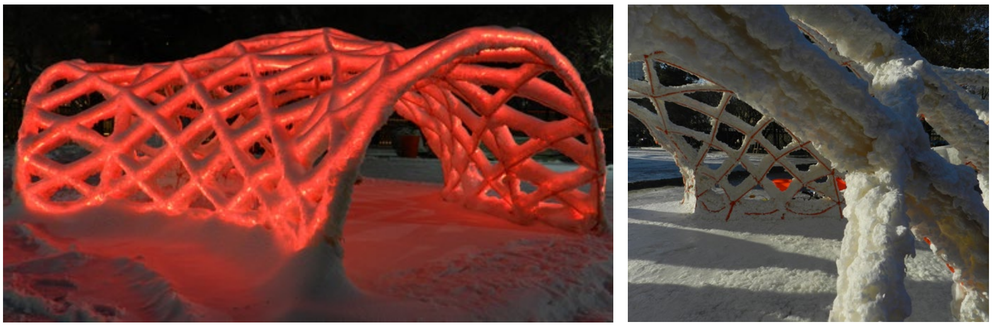


Figure 5: The final result of the constructed grid shell in ice in Harbin, China, and a close-up image of the printed cross-section of a grid member.

7. Discussion

This paper presents research regarding the design and execution of a grid shell structure in reinforced ice constructed by means of a 3D printing process. The main issues related to this topic included the research into the material properties of reinforced ice, the form-finding process of the grid shell design, the research into the formwork that was used during the execution of the grid shell and the investigation of 3D printing techniques to extrude layers of ice. The combination of all the different studies presented in this paper resulted in the development and the construction of a final grid shell design.

This grid shell in ice was successfully designed as can be seen in Figure 5. The gridshell had inward curved supports that seem to contribute to the high stiffness of the structure. It should be noted that the assumed positive influence of inward curvature of the supports was based on literature [10], and it was only checked with a basic calculation in ABAQUS. Further research is necessary to verify this initial calculation. After the final shape of the grid shell was determined, the grid was optimized to enhance the force distribution in the structure. The results of a FEM analysis showed that the final grid shell had sufficient capacity to withstand a substantial additional loading of approximately 6000 kg, next to self-weight. The high stiffness of the structure could possibly be attributed to the variety in grid density applied in accordance with the expected stress distribution. Although the final models for the self-weight calculation with and without additional loading implied simplifications regarding the structural configuration, the results were assumed to be reliable. Further research should target more accurate calculations to predict the structural behaviour of a grid shell subjected to asymmetric loading and a grid shell during construction. If in future projects the size of the grid shell is increased, a grid shell with a triangular mesh will likely be more feasible. In addition, if the manual printing process becomes labour-intensive for large-scale projects, an automated printing process is then probably more desirable.

8. Conclusion

The results presented in this paper indicate that an ice composite grid shell structure can be designed and verified with the help of computer software such as Rhinoceros, Grasshopper and ABAQUS. By combining these software tools, engineers can perform an iterative design process in which a suitable overall shape and grid morphology can be modelled and analysed. The shape of the inflatable mould designed by the TU/e team guided the form finding phase of the grid shell. The structural analyses in

ABAQUS helped to determine the optimal shape and grid morphology by minimizing the overall deformations and the peak stresses in the structure. If engineers in future projects construct their digitally designed and verified structure on an inflatable mould by means of a manual 3D-printing process, it will probably result in a successful end-product that is sufficiently strong to carry both its own self-weight as well as a substantial additional load.

Acknowledgements

The TU/e design team wants to thank the following for their contribution to this project: the 'Harbin Institute of Technology' (HIT) in China for organizing a competition for structural ice, and for arranging a building site for the construction of the grid shell; Elke Mergny for her guidance and advice on modelling in ABAQUS and her extensive reviews on our numerical results; and the employees of the structures laboratory and ice researchers of the TU/e for their help and support.

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