Form-finding and construction of ice composite shell structures

Wu, Yue; Liu, Xiuming; Li, Qingpeng; Chen, Boxuan; Luo, Peng; Pronk, Arno; Mergny, Elke

Publication date
2017

Document Version
Final published version

Published in
Proceedings of the IASS Annual Symposium 2017

Proceedings of the IASS Annual Symposium 2017
"Interfaces: architecture . engineering . science"
September 25 - 28th, 2017, Hamburg, Germany
Annette Bögle, Manfred Grohmann (eds.)

Form-finding and construction of ice composite shell structures

Yue WU[a], Xiuming LIU[a], Qingpeng LI*, Boxuan CHEN[a], Peng LUO[b], Arno PRONK[c], Elke MERGNY[d]

* Key Lab of Structures Dynamic Behavior and Control of China Ministry of Education, Harbin Institute of Technology, Harbin 150090, PR China
Faculty of Architecture and Built Environment, Delft University of Technology, Julianalaan 134, 2628 BL Delft, The Netherlands
hitssrclqp@gmail.com

[a] Key Lab of Structures Dynamic Behavior and Control of China Ministry of Education, Harbin Institute of Technology
[b] School of Architecture, Harbin Institute of Technology
[c] Department Built Environment, Eindhoven University of Technology
[d] Faculty of Applied Science, ARGENCO Department, University of Liege

Abstract

By using inflatable moulds and then spraying cellulose-water mixture, one ice dome and two ice towers were built in Harbin in December 2016. During the whole process, form-finding of the inflatable moulds as well as the construction of these ice composite shell structures are very important for the final results.

The mould for the ice dome structure was a result of the manipulation of a synclastic membrane with a rope net. The mould for the ice tower structure consisted of some anticlastic surfaces. Form-finding of the inflatable moulds was conducted by the parametric tool "EasyForm" which is a self-programed plug-in in Grasshopper based on Vector Form Intrinsic Finite Element method.

In a low-temperature work environment (-10 ℃ and below), the ice shell structures were constructed on the inflatable moulds. The cellulose-water mixture was sprayed in thin layers continuously and uniformly in order to make the surface of a shell of cellulose-reinforced ice. The construction process is introduced detailedly in this paper.

Keywords: Ice composite shell, form-finding, Vector Form Intrinsic Finite Element, construction, inflatable mould, cellulose-reinforced ice

1. Introduction

There has been a long history of making ice structures. Heinz Isler realized some experiments since the 1950s [1]. Kokawa created several ice domes in the north of Japan with a span up to 25 meters in the past three decades [2]. Coar realized a number of fabric formed ice shell structures by using fiberglass bars and hanging fabrics as a mould for an ice shell in 2011, and in 2015 he produced a fabric formed ice origami structure in cooperation with MIT (Mueller) and VUB (De Laet) [3]. Pronk realized several ice composite structures with inflatable moulds in 2014[4], 2015[5] and 2016 [6], .

In December 2016, one dome and two towers of cellulose-reinforced ice were built in Harbin (China) in a cooperation between Harbin Institute of Technology (Wu and Luo) and Eindhoven University of Technology (Pronk). By using inflatable membranes as the construction moulds of the ice shells, the construction process is much simpler and more feasible.

At present, the increasingly complex architectural forms bring great challenges for the design of the inflatable mould. How to design the inflatable mould with required constraints is the key problem that needs to be solved urgently, according to the design of the complex surface ice shell given by the architect. Reasonable stress distribution and construction feasibility during the spraying of the ice composite materials are considered as constraints for inflatable moulds of ice shells.

Based on the Vector Form Intrinsic Finite Element (VFIFE, for short) method [7], a self-programed plug-in in the platform of Rhino-Grasshopper, named as “EasyForm v1.2”, was developed by Wu, Liu and Li to realize form-finding of freeform structures. In this paper, the parametric tool was used to conduct form-finding analyses of the inflatable moulds of the two ice shell structures. After the design work, in a low temperature (below -10°) construction environment, with the inflatable membranes as the construction moulds, by means of continuously and uniformly spraying cellulose-water mixture, the two ice composite shell structures were finally constructed successfully. Some influence factors are introduced here.

2. Architectural design of the ice shells

The structural efficiency of shell structures depends mainly on their shapes. In well-designed shells, membrane forces are dominant and only small bending moments occur. Therefore, how to generate structurally efficient form of the structure in the structural design stage has become the key problem to be explored. By considering this problem, Van Hennik and Houtman [8] summarized several guidelines for the design of shell structures, which are as follows (Figure 1):

- Avoid small curvatures and thus almost flat parts.
- Try to avoid single curved and thus cylindrical parts.
- Accordingly, strive for double curvature, whether it is synclastic or anticlastic.
- Observe the anti-ponding theory or anti-water-collection theory.
- Avoid large openings at a right angle to the shell.

Figure 1: Design guidelines for irregular double curved shell [8]

Based on the above shell design guidelines, the architects designed two ice shell design schemes which were greatly different from the traditional simple mathematical shapes. These two designs tried to broaden the usage of ice composite as building materials, and to challenge the construction of more complex and novel ice shell structures. The following is a brief introduction to the architectural design of the two types of ice shells.

1) The ice tower was a modern design with a flamenco skirt (shown in Figure 2) and a traditional Chinese tower. The design consisted of a 4-meter vertical tower and six "skirt" entrance, shown in Figure 3. This "skirt" modeling was elegant with anticlastic surfaces.
2) The idea of the design of the ice dome came from the Chinese Tianshan Snow Iotus (shown in Figure 4). The snow lotus was considered as auspicious signs, representing holy love and perseverance. The design model consisted of 12 inversed petals, with the height of 4.3 meters and the span of 11.0 meters, shown in Figure 5.

Figure 2: Flamenco dancer

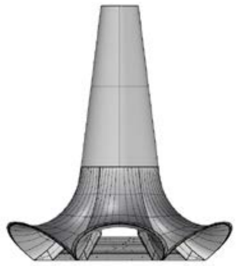

Figure 3: The design scheme of the ice tower

Figure 4: Snow Itus

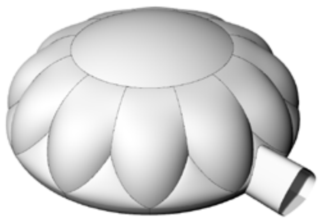

Figure 5: The design scheme of the ice dome

3. Form-finding of inflatable moulds

3.1 The shape of inflatable moulds

Van Hennik and Houtman [8] also recommended the following several principles for the shape design of the pneumatic formworks (Figure 6):

- A higher pressure causes a greater volume and a smaller radius.
- Basically, pneumatic structures cannot be formed in rectangular shapes.
- Basically, pneumatic structures cannot have opposite synclastic shapes.
- The height depends on shape of edge.

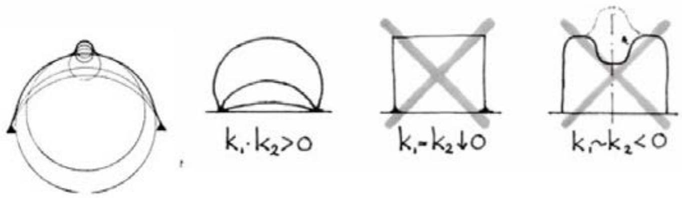

Figure 6: Principles for designing pneumatic formworks [8]

In order to achieve a novel shape, the inflatable moulds can be manipulated with irregular shaped edges, point supports, inner walls or cables. In this paper, taking the ice dome as the case study, design and form-finding of the inflatable mould are introduced.

Compared with tension membrane structures, the inflatable membrane analysis is much more complex due to the existence of internal pressure. The vast majority of the inflatable membrane structures of the actual projects are not equally stressed curved surface, in addition to the standard spherical or cylindrical surface. Even if there is an equally stressed curved surface, the shapes of moulds mostly cannot meet the functional requirements. Because of the absence of the equally stressed curved surface, the final form-finding results usually keep a close relationship with the initial shape of the inflatable structures. In order to realize the "petal" design of the ice dome, it is necessary to add cables to strengthen the restrictions which plays a role in constraining the deformation of the inflatable membrane. Figure 7 shows the initial shape of the membrane and the layout of cable net.

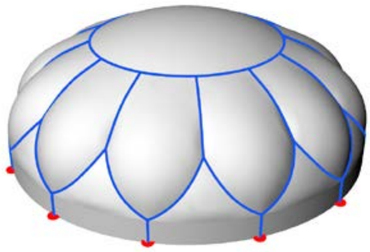

Figure 7: Initial shape of the membrane and layout of cable net

3.2. Vector Form Intrinsic Finite Element

The VFIFE method is a relatively new numerical analysis method. Other than the traditional numerical analysis methods which are based on continuum mechanics and variational principles, VFIFE is based on point value description and the vector mechanics theory. With the description of point values and path units, VFIFE describes the structural system composed of particles whose motions are determined by Newton's second law. Shown in Figure 8 is the flowchart of the VFIFE method. During the calculation procedure, there is no need to integrate the structural stiffness matrix, and it can increase (or decrease) elements or change any property of the structural system. Therefore, VFIFE has a remarkable predominance in nonlinear problems and complex behaviors of structures compared with the traditional numerical analysis methods. VFIFE can be also used in the field of form-finding research, Li et al. [7] applied VFIFE to carry out form-finding of shells which are generated from three types of physical models, such as hanging models, tent models and pneumatic models.

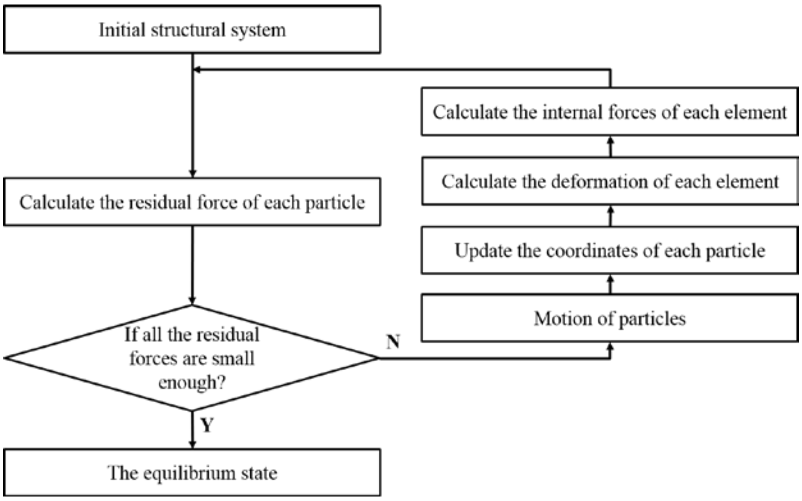

Figure 8: Flowchart of the VFIFE

3.3. The EasyForm

The VFIFE is applied to the Rhino-Grasshopper parameterized platform by the authors[9], and the form generation system EasyForm V1.2 (Figure 9) which can be used to generate the form for freeform structures is developed. In this system, designers or structural engineers only need to adjust the corresponding parameters to achieve the whole form-finding process including "initial modeling" – "numerical analysis" – "post-processing". On one hand, compared with the former work (initial modeling in AutoCAD and then numerical analysis in MATLAB), the EasyForm V1.2 greatly reduces the complexity of the work, effectively improves the efficiency of structural design by saving the time of data conversion between different softwares. On the other hand, the parametric modeling ideas are also introduced in this system which is conducive to engineers to modify the structure by adjusting the input of new parameters. Moreover, the calculation efficiency of the EasyForm V1.2 is greatly improved by using compiled programming language and parallel computing on the program.

The EasyForm V1.2 system is developed by using the *C#* programming language based on the *.NET Framework 4.0* framework, and compiled in the *Visual Studio 2015* platform. EasyForm V1.2 mainly includes three modules, such as the pre-processing module, the computing module and the post-processing module. In addition, the system has a series of features, such as visual programming interface, fast computing speed, exception handling, late expansibility and etc.

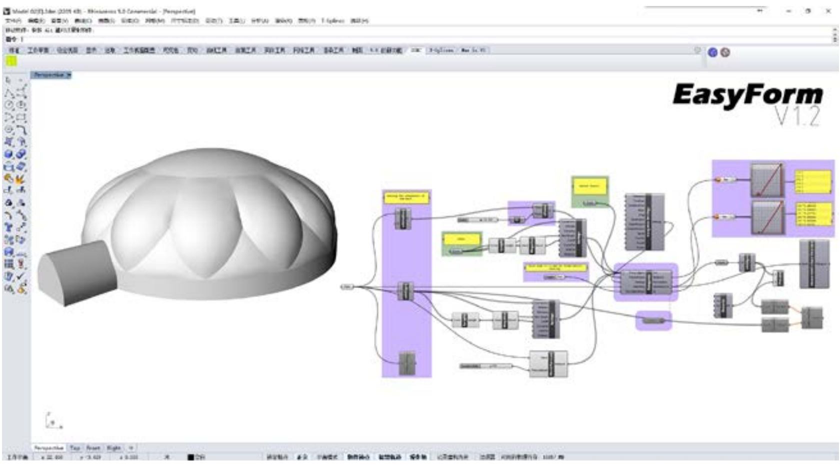

Figure 9: EasyForm v1.2

3.4. Form-finding of the inflatable mould of the ice dome

According to the initial architectural design, the height of the inflatable mould is 4.3m. The basic assumption is that there is no relative slip between the cable and the membrane. The discrete nodes of the membrane element coincide with those of the cable element, so the imbalance force of the node is the residual forces of internal force of the membrane, that of the cable element and the internal pressure loads. It is necessary to control the form-finding process of the inflatable mould.

After several iterations, the final result of the inflatable film satisfying the control height of 4.3 m can be obtained shown in Figure 10, in which the blue curves represent the initial design shape of the inflatable mould, and the red part is the final equilibrium inflatable mould. By comparing the results before and after form-finding, it is found that there is a significant bulging in the connection area of the "petal" of the inflatable membrane. Although the effect of the cables works, it is still not satisfied. The main reason is that the direction of the cable force is approximately perpendicular to that of the pressure load (Figure 11). Therefore, curvature occurs in this part to keep equilibrium. For next step, it is possible to resist the deformation of the membrane by internally adding a cable approximately parallel to the pressure load (Figure 12).

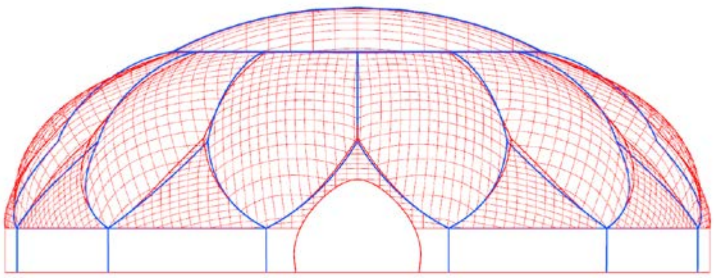

Figure 10: Form-finding of the inflatable mould of the ice dome

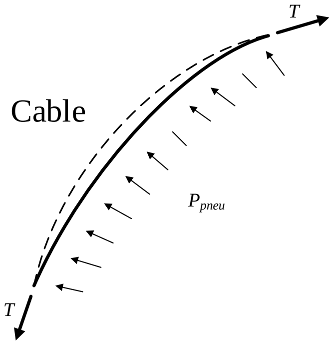

Figure 11: The force diagram of the cable and the membrane

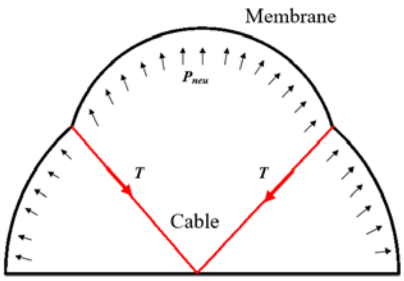

Figure 12: The force diagram of the cable and the membrane by adding internal cables

4. Deformation and pressure control of inflatable membrane moulds

There is a long history of the design and construction of inflatable membrane structures, and many design specifications have been developed, for instance, the Chinese Technical specification for membrane structures (CECS 158: 2015) [10], the Japanese specification [11] and IASS design guidelines [12]. The internal pressure of the inflatable membrane structure should be corresponding to the external loads of the structure to maintain the stable equilibrium state of the structure. CECS 158: 2015 indicates that the normal working pressure of an air-supported membrane structure should not be over 300 Pa. The Japanese specification specifies that the internal pressure should be greater than 200 Pa during normal operation.

For the inflatable mould of the ice shell, its internal pressure should be greater than the sum of the normal working pressure and self-weight of the ice composite material. In this case can it ensure the stability of the membrane surface, and avoid local depression of the membrane. Once the local depression develops by the reason of accumulation of ice materials, it would be difficult to eliminate by increasing the internal pressure. So it is very important to ensure that the membrane does not appear local depression, which is not only related to the internal pressure setting, but also closely related to the equilibrium shape of the membrane.

The deformation of the inflatable mould during the construction process of spraying cellulose-water mixture is complex. At present, there is no calculation and analysis of the inflatables due to the lack of air pressure or overpressure. Sobek [13] discussed the deformation of the inflatable mould caused by the spraying concrete during construction of reinforced concrete shells. Compared with the traditional concrete materials, the development of the strength of ice composite is totally different. General concrete needs a longer period of time to cure (usually more than 28 days), so for the load analysis of the inflatable mould, the full thickness of the concrete should be considered as the load case. For the construction of spraying ice composite, the maximum strength of the ice material can be achieved after the solidification of the liquid water. Therefore, for the load analysis of the inflatable mould of ice shells, it would be conservative when considering the full thickness of the ice shell. When the ice on the surface of the inflatable mould reaches a certain thickness (about 5.0 cm), the ice shell itself can resist its self-weight and the loads due to the spraying of liquid ice composite material.

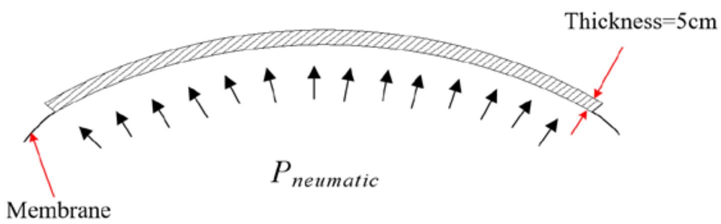

Figure 13: The load analysis of the inflatable mould and the ice shell

Assuming that the density of the ice composite material is 980 Kg/m^3, and the thickness of the ice shell is 5.0 cm, as shown in Figure 13, a simple estimate of the pressure of the inflatable mould would be 500Pa.

5. Construction of ice composite shell structures

In this paper, the inflatable mould is introduced into the construction process as the formwork of the ice shell structure. By continuously and uniformly spraying the cellulose-water mixture on the outer surface of the membrane, and after the spraying material on the surface of the mould is cooled and solidified, then the inflatable mould can be remove slowly, and thus the ice shell is constructed finally. Specifically, the construction process of the ice shell is mainly introduced in the following order.

5.1. Inflation of the membrane mould

According to the design of the cable network layout, the connections of the cable net can be completed. The joint of the cable are connected by U-shaped buckles, as shown in Figure 14. Then the inflatable mould was inflated with an internal membrane pressure of 50~60Pa. When the inflatable mould is basically filled, the tilt phenomenon occurred in the bottom part, then the ice ring beam is needed to be built before the spraying of ice composite material (Figure 15).

Figure 14: The joint connection of the cables

Figure 15: The ice ring beam

5.2. Spraying cellulose-water mixture

Gradually improve the pressure inside the membrane, and ensure that the internal pressure within the stage of 400Pa (Figure 16). This is to ensure that large deformation of the inflatable mould would not occur, and to improve the ice shell condensation rate. After the internal pressure was stabilized, the spraying of the cellulose-water mixture were debugged and sprayed. This test uses 1% of cellulose-reinforced ice material, not only to ensure the strength of ice material, but also to meet the pipeline pumping requirements to prevent clogging the pipelines. It is found that the adhesion of ice composite material on the membrane surface is good enough (Figure 17), which is mainly due to the low air temperature and humidity in Harbin, which improves the freezing rate of ice material, and thus accelerates the construction efficiency of the ice shell.

Figure 16: Pressure control equipment

Figure 17: Attached ice on the inflatable mould

5.3. Removal of the inflatable mould

After achieving the desired design thickness, and a period of time of cooling and soliding, the inflatable mould can be removed from the ice shell. As the surface of the inflatable mould and the ice shell had a certain interaction between the bond, and the density of PVC membrane material is high, direct depressurization to zero would bring a larger additional load to the ice shell. Based on this consideration, this depressurization of the internal prssure of the inflatable mould was done slowly as shown in Table 1. During the stage of depressurization, the inflatable membrane is gradually removed from the ice shell (Figure 18) in order to minimize the additional loads of the ice shell.

Tab.1. Slope pressure control mode

Time	Pressure control（Pa）
9:00	150
10:00	100
10:30	75
11:00	50
12:00	0

Figure 18: Removal of the inflatable mould

Finally, after the construction work of 14 days, these projects were constructed successfully, show in Figure 19.

Figure 19: The three ice structures in Harbin, China, 2016

6. Conclusions

In this paper, the design guidelines of the complex curved surface of the ice shell and the design of the inflatable mould are discussed. According to the design guidelines and the morphological relationship of the shell structure, two complex ice shell structures are designed and constructed.

In order to solve the strong non-linear characteristics of numerical analysis of complex inflatable mould, a free-form structural form generation system, EasyForm V1.2, is developed. This system is based on the VFIFE method and is used to conduct form-finding of these inflatable moulds of ice shells in this paper.

Due the complex deformation of the inflatable mould in the construction process, how to set a suitable inflatable mould pressure becomes the key issue to be explored urgently. Based on the design thickness of the ice shell, the magnitute of the internal pressure of the inflatable mould is given to meet the construction requirements of the ice shell.

The construction process of the ice composite shells is introduced in detail, including inflation of the membrane mould, spraying of the cellulose-water mixture, and removal of the mould.

It is the first time to construct this type of ice structures with ice composite materials in China.

Acknowledgements

The work has been supported by the National Natural Science Foundation of China (Grant No. 51378150 and Grant No. 51578186).

References

[1] Chilton J., *The Engineer's contribution to contemporary architecture: Heinz Isler*, Thomas Telford Publishing, London, 2000.

[2] Kokawa T., State of the Art Developments in Ice Shell Construction, in *Proceedings of 17th Canadian Hydrotechnical Conference*, Edmonton, Canada, 17-19 August 2005: 973-982.

[3] Coar L, Mueller C, Laet de L, Hare J, Wiese K, Oberlin S., Fabrigami: Design and fabrication of an origami-inspired ice and fabric shell, in *Proceedings of the International Society of Shell and Space structures*, Tokyo, Japan, 26-30 September 2016.

[4] Pronk A.D.C., Borgart A., Hijl J.M., Pluijmen R.M.F., The calculation and construction of a 30 meter span ice dome, in *Proceedings of the IASS-SLTE 2014 Symposium*, Brasilia, Brazil15 - 19 September 2014.

[5] Pronk A.D.C., Verberne T.H.P., Kern J., Belis J., 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, The Netherlands, 16 - 17 August 2015.

[6] Pronk A.D.C., Arntz M.H.F.P., Hermens L., Da Vinci's Bridge in ice and other ice structures with an Inflatable mould, in *Proceedings of the IASS Annual Symposium 2016*, Tokyo, Japan, 26-30 September 2016.

[7] Li Q., Su Y., Wu Y., Borgart A., Rots J.G., Form-finding of shell structures generated from physical models, *International Journal of Space Structures*, 2017, 32(1): 11-33.

[8] Van Hennik P. C., Houtman R., Pneumatic formwork for irregular curved thin shells, in *Textile Composites and Inflatable Structures II*, Springer, 2008: 99–116.

[9] Wu Y., Liu X., Chen B., Li Q., Structural generation system of freeform structures based on the platform of Rhino-Grasshopper, in *Proceedings of 16th Academic Conference of Space Structures in China*, Hangzhou, China, 2016. (in Chinese)

[10] CECS 158-2015. Technical specification for membrane structure. 2015. (in Chinese)

[11] Membrane Tectonics Association, Membrane Structure, Building Structure. 1994. (in Japanese)

[12] Recommendations for the Design of Air Supported Structures, IASS, 1986.

[13] Sobek W., Auf pneumatisch gestutzen Schalungen hergestellte Betonschalen, Verlag Ursula Sobek, Stuttgart, 1987.