ICE SHELL - REVIEW AND RECENT APPLICATION

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SUMMARY

ICE SHELL is thin, and its structural material is snow-ice. It may be considered as a contemporary "Igloo in Eskimo" or "Kamakura in Japan". It can cover by far a large area compared with these classical snow-ice structures, because of the high structural efficiency. It creates a fantastic and beautiful space and may provide an efficient architectural solution to certain problems in the snowy and cold regions during winter. This paper describes 1) looking back upon the study of ice shell developed in Asahikawa for the last 20 years concerning with structural and constructional engineering, and 2) recent architectural application for winter leisure spaces covered by many ice shells including a large free-shape ice shell and 20 m span ice dome, at Tomamu in Hokkaido.

Keywords: *Ice structure, Pneumatic formwork, Snow blowing, Water spraying, Winter architecture.*

1. INTRODUCTION

Snow and ice have been long used as structural materials for constructing the temporary enclosures in snowy and cold regions. Floating ice-platform to support offshore drilling operations on the arctic sea [1], ice bridges for heavy transportation [2] and ice-plate on a river for the railway track during the World War II [3] are well known as the examples of civil engineering structures. On the other side, the ice shell is suggested as one of the architectural structure, as seen in the example of "igloo in Eskimo" or "kamakura in Japan". The ice shell is also a kind of ice structure and may be considered a contemporary "igloo" or "kamakura". The ice shell is thin, and its structural material is snow-ice. It is a new type of ice structures based on the modern structural engineering and it can cover by far a large area compared with the classical snow-ice structures. It creates a fantastic and beautiful space and may provide an efficient architectural solution to certain problems in the snowy and cold regions during winter.

As written in a previous paper [4], aiming at the production of ice shells with spans from 20 to 30 m, which could be used for a variety of expedient shelters, we started the studies on both structural safety and construction method of an ice shell at the beginning of 1980's. This paper describes 1) looking back upon the study of ice shell developed in Asahikawa for the last 20 years concerning with structural and constructional engineering, and 2) recent architectural application for winter leisure spaces covered by many ice shells including a large free-shape ice shell and a 20 m span ice dome, at Tomamu in Hokkaido.

2. PREVIOUS DEVELOPMENT

A. CONSTRUCTION METHOD

A.1. Outline

The physical environment of Asahikawa district becomes severe in winter. The average air temperature in January and February is about -8°C, the yearly total number of ice days is about 80, and the yearly mean maximum snow depth is about 90 cm. The severe environment makes the realization of ice shell possible, although the term of practical use is limited to three months at the longest during winter in Asahikawa.

"Kamakura" or "Igloo" is well known as a classical snow-ice structure, but it seems that these structures do not have both construction rationality and structural efficiency in the case of a large span. "Kamakura" is a Japanese traditional snow hut where children play house in Shogatsu, constructed by scooping out the snow from a small snow mountain.

"Igloo" is a snow house for Eskimo constructed by heaping up snow blocks hemispherically. On the other side, the ice shell is constructed by the following method, which satisfies fundamentally the facility of a rapid, easy and economical construction:

1) Building up the 3-dimensional formwork by inflating a 2-dimensional membrane bag covered with ropes anchored to the snow-ice foundation.

2) Covering the membrane with thin snow-ice sherbet by blowing the milled snow with a rotary snow-plow and spraying tap water with a high pressure adjustable nozzle. Solidifying the thin layer snow-ice sherbet due to cooling by cold outside air.

3) Repeating the application of snow and water up to the desired shell thickness. Then removing the bag and ropes for reuse.

4) If the inside light sufficiently transmits through the completed shell, it is judged the shell have a good quality of ice.

A.2. Feature of pneumatic form

One of the most featuring things in this construction method is concerned with the form finding method by the air-inflated formwork. The formwork consists of the membrane and covering ropes. The ropes play an important role in forming the shape of the air-inflated membrane. The tension in the ropes is equilibrated by the force in the air-inflation. The membrane does not need the 3-dimensional cutting, owing to the force control by the covering ropes. So, the membrane is easy to fabricate, even though the 3-dimensional form is complicated. It is supposed many different forms come from the same membrane by changing the length and geometric pattern of ropes. Because these forms are decided automatically under the uniform pressure, the completed ice shell works mainly in compression membrane force, in spite of free-shape shell. So, this structure makes the best use of the ice material which is strong enough for compression force. Furthermore, its general form chosen automatically by this method is regularly consisted of same convex patterns. A family of reinforced ribs with large sectional areas along the ropes brings not only the improvement of structural efficiency, but also the geometrical beauty at the inside surface.

A.3. Snow blowing and water spraying

In order to produce quickly a high quality of ice on the membrane, some devices are needed. Snow is blown onto the membrane by a rotary snow-plow and tap water sprayed on the snow by a high pressure adjustable nozzle. The snow is called "milled snow" which has a strong bond like a ceramic. A snow-ice sherbet produced on the membrane, is frozen hard some time later under the air temperature -10°C below. It is necessary during one blowing operation to keep the milled snow depth to be less than about 1 cm thickness. Otherwise, when water is sprayed, only the snow surface solidify and the membrane cannot hold the form because of excessive weight which cause material and geometrical imperfections as previously reported [5]. The snow-ice sherbet solidifies more quickly than only water because of the low latent heat, and the ice seems to be more ductile. It normally takes 1.5 hour to get 1 cm thickness. When the ice thickness reaches to an amount, the ice itself can support the weight of a new snow-ice sherbet layer instead of the inflated membrane. Therefore, the membrane does not need a high pressure and the formwork including the foundation becomes lightness and low cost. The application of snow and water are repeated up to the desired shell thickness which is normally about 1/100th of the span.

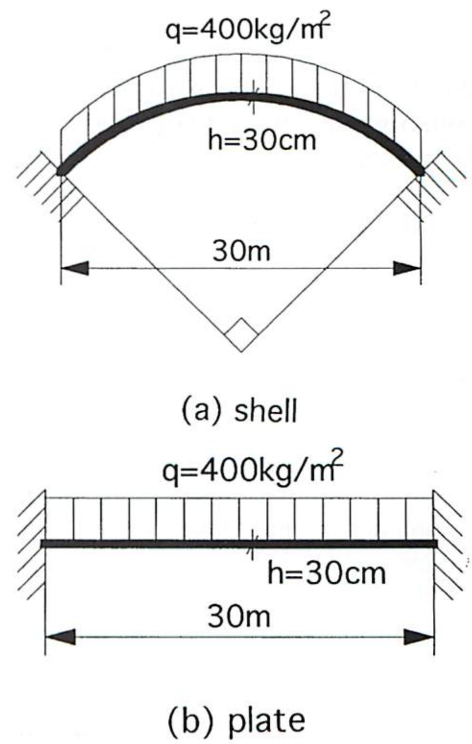

Fig. 1. Comparison of structural efficiency between shell and plate

B. STRUCTURAL SAFETY

B.1. Elastic consideration

As is generally known, thin shell structures usually have enough stiffness and load carrying capacity in comparison with their own weight, and are used for wide span roofs in architecture. By comparing the mechanical properties of a flat plate and a spherical shell, each with 30 cm thickness and 30 m diameter (90 degree open angle in case of the shell) as shown in Fig. 1, it can be understood how shell structures have a superior structural efficiency. Comparisons of stress and deflection are made at the central point of these structures, based upon the membrane theory in case of the shell and the thin plate theory in case of the flat plate [6]. The results are as follows. (1) $\sigma p/\sigma s=37$, where σs, σp are the stress of the shell and the plate, respectively. With a vertical load of $q=400$ kg/m^2, σs becomes 1.4 kg/cm^2 in compression which is about 1/30th of the uniaxial compressive strength of snow-ice. (2) $\delta p/\delta s=273$, where δs, δp are the vertical displacement of the shell and the plate, respectively. If Young's modulus $E=5$ t/cm^2, δs becomes 6.0 mm. From these brief discussions, it is supposed a relatively large ice shell will be able to exist theoretically, although no consideration on the creep problem of the structure.

B.2. Creep behaviour

The strength of an ice shell is sufficient for some given loads over a short period. However, as the snow-ice creeps, it is important to investigate the creep behaviour of an ice shell which will experience loads for a long time. So, experiments on ice domes with 60 cm [7], 2 m [8], 5 m [4] spans under long-term loading, and the axisymmetric creep buckling analysis of ice domes [9], were conducted together with the beginning of investigations on the structural safety. And then the experimental creep test of 10 m [4], 15 m [10] and 20 m [5] span model which were constructed based on the prescribed method, were carried out carefully. As the important result of these tests, it is confirmed that ice shells produce a large creep deformation slowly before the collapse, as shown in Fig. 2 [4]. It indicates also that the collapse does not occur abruptly, and we have enough time to predict the danger of the collapse. The ductile behaviour gives the reason why ice shells are possibly used as architectural structures.

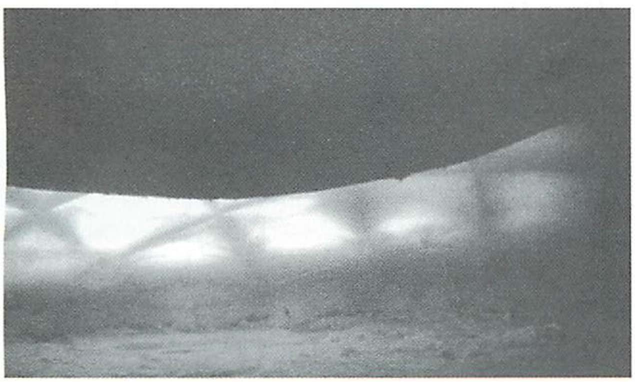

Fig. 2. Deformation at onset of collapse

3. RECENT APPLICATION

A. PROJECT IN TOMAMU

Before and after the prescribed investigations, on account of both the easy construction technique and high durability, for the past decade, 10 m span small ice dome have been practically used for a variety of temporary shelters such as a winter storage of vegetables, a factory house for making Japanese "sake", an exhibition hall for a winter festival and a working space at the basement-area for Japan Observatory in the South Pole. Passing through these experiences, we have been in a chance to construct large-scaled ice shells for an architectural space in Tomamu where has more severe winter than Asahikawa, Hokkaido, since 1997. A lots of ice shells have been constructed there as shown in Fig. 3 by Hotel Alpha Resort Tomamu people, and the ice shells have been used as leisure spaces for tourists during about 3 months in each winter. Among them, the design and construction processes of a large free-shape ice shell and a 20 m span ice dome which were never seen before, are described with pictures following.

B. LARGE FREE-SHAPE ICE SHELL

It is easy to set up a 3-dimensional formwork consisting of a 2-dimensional membrane bag and a covering net, as previously mentioned in section "Feature of Pneumatic Form". So it is possible to construct a free-shape shell which has both structural rationality and artistic beauty. The shell has a comma-shaped heraldic plan with the same area as the circle of 15 m diameter. Fig. 4 shows the situation of measuring 3-dimensional coordinates on the surface of 1/20 scaled model consisted of a vinyl-membrane and a fishing-net. The data were used for the Finite Element Structural Analysis under gravity

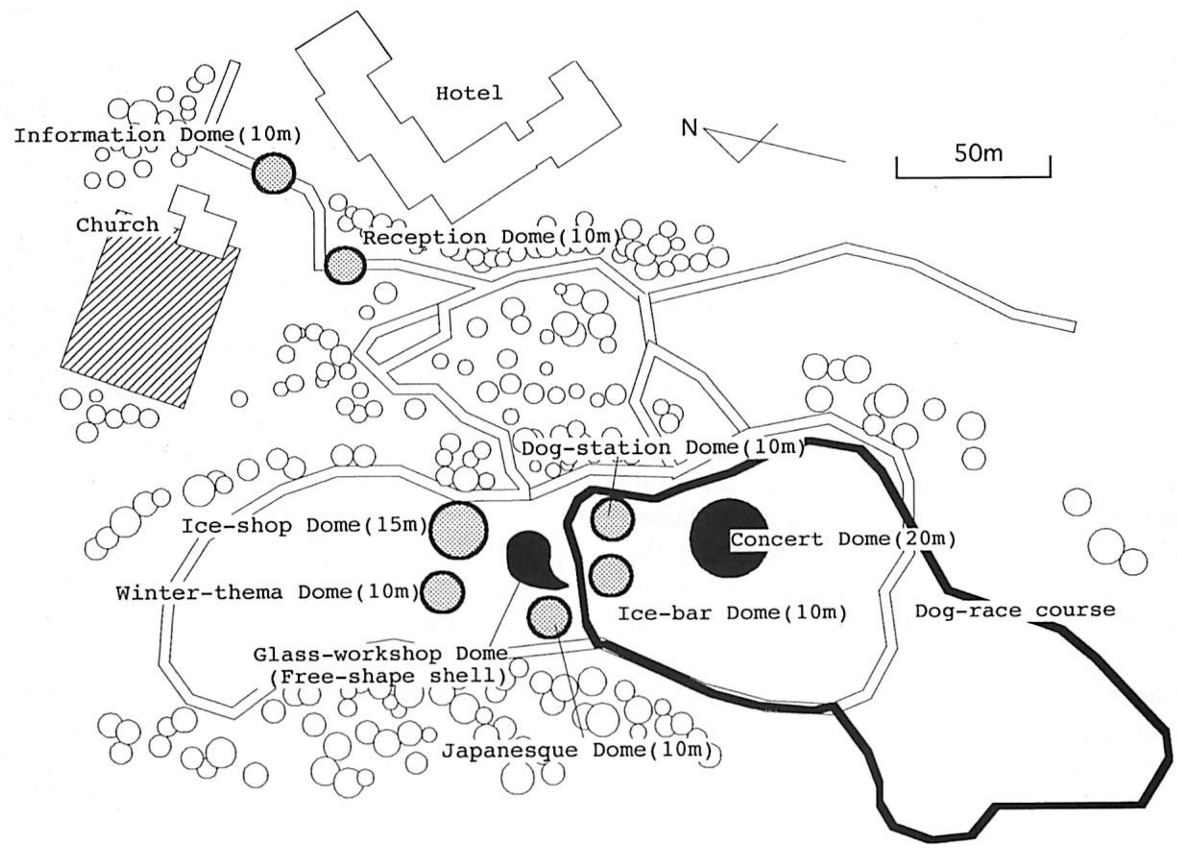

Fig. 3. Ice Shells in Tomamu (1998-1999 winter)

load, and it confirmed that the construction of the shell would be possible because the maximum compression stress was less than 1 kg/cm^2. Fig. 5 shows the full-scaled pneumatic formwork at the site. The maximum height is about 4.5 m. The formwork consists of a P.V.C. membrane and 10 mm diameter Polypropylene ropes which are laid orthogonally on the plane projection. Fig. 6 shows the snow blowing by a rotary snow-plow and tap water spraying by a adjustable nozzle, onto the formwork. As the result of this operation, a snow-ice sherbet is produced on the formwork, and it is frozen hard some time later under the air temperature below -10°C and the radiation heat loss over night. In order to avoid material imperfections, the milled snow depth per one blowing operation is less than 1 cm. It took 1.5 hour to get 1 cm thickness ice through this construction. The application of snow and water are repeated up to 15 cm thickness in average. The pneumatic formwork is deflated after that, and then we met a beautiful half-transparent inside space covered by a thin-curved wall with rib stiffeners, as shown in Fig. 7. The inside space was used as a manufacturing room where tourists make

Fig. 4. Measuring geometry 1/20 scaled model

Fig. 5. Formwork for free-shape shell

Fig. 6. Snow blowing and water spraying

Fig. 7. Inside after removing membrane

Fig. 8. Inside for a glass-craft room

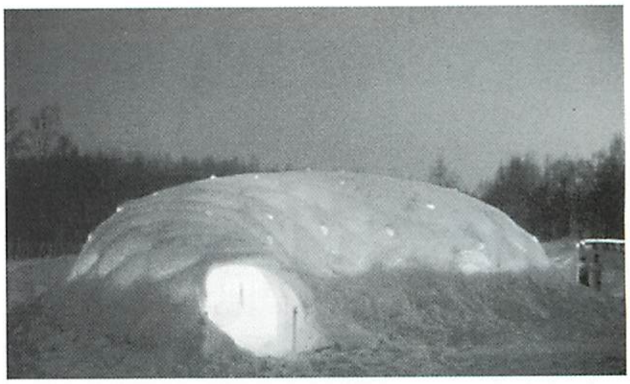

Fig. 9. Exterior view

an ice-glass from an ice block, as shown in Fig. 8. Fig. 9 shows the exterior view which is lighten up from the inside. It is judged that the completed shell has a good quality of ice.

C. 20 M SPAN ICE DOME

It was the winter of 1985 when we tried for the first time to construct a 20 m span ice dome. As discussed in the paper [5], geometrical and material imperfections of the constructed dome were observed because of the unskilled snow blowing operation and, as result, the structural behaviour was not good. In this time we had again the chance to construct the same size of a 20 m span ice dome in Tomamu. After the snow-ice foundation ring was finished, the dome was carefully constructed during February 6th-8th in 1999. Fig. 10 shows the reticulated pattern of the covered ropes based on a geodesic division. The polypropylen ropes has 14 mm diameter, and equal length of 1.5 m between points. Fig. 11 shows the inflated formwork which has about 6.5 m in the central height. Fig. 12 shows the situation of the snow blowing by a rotary snowplow and tap water spraying by a adjustable nozzle, onto the formwork. The spraying water onto the vicinity of the apex, was carried out by preparing a

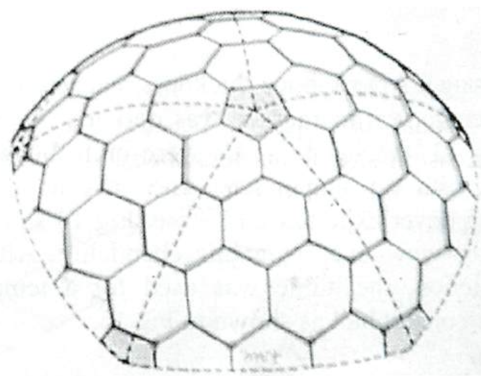

Fig. 10. Reticular pattern by geodesic division

Fig. 11. Air-inflated membrane as formwork

Fig. 12. Snow blowing and water spraying

Fig. 13. Inside during deflation

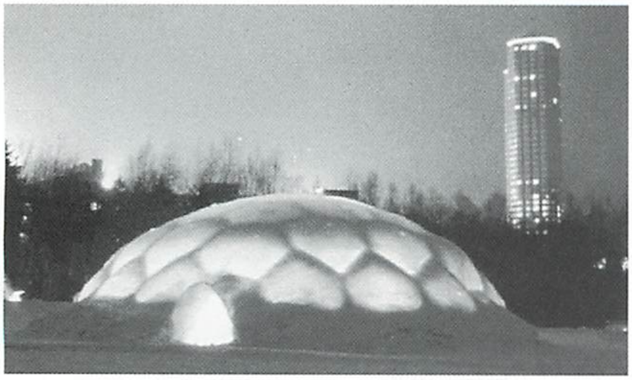

Fig. 14. Exterior view

Fig. 15. Inside space for concert hall

high stage. After the ice thickness reached to 15 cm in average, the membrane was deflated. As shown in Fig 13, the inside space were quite huge compared with the human scale and gave us a space-feeling never experienced before. Fig 14 shows the exterior view like a gigantic chandelier. After the completion, the dome was used for a temporary music concert hall as shown in Fig 15.

4. CONCLUSION

Snow and cold brought an existence of the ice shell which may provide a quite unique built environment in the snowy and cold regions. Our study started at the beginning of 1980's, aiming at the production of 20~30 m span ice shells for architectural structures during winter in Hokkaido, Japan. Based on the results of study for the past 20 years, the realization of a 30 m span ice shell comes basically within our reach, although the reliability of its structural safety and improvements of the construction technique are needed much more by the untiring studies.

REFERENCES

[1] Baudais D. J., Masterson D. M. and Watts J. S., 'A system for offshore drilling in the Arctic Islands', J. Canadian Petroleum Technology, 13, 3, 15-26, 1974.

[2] Michel B., Drouin M., Lefebvre L. M., Rosenberg P. and Murry R., 'Ice Bridges of the James Bay Project', Can. Geotech. J., 11, 1974, 599-619.

[3] Kubo Y., 'Introductory Remarks on Iceological Engineering (in Japanese)', Tairyusha, 1980.9, 42-90.

[4] Kokawa T., 'Experimental studies on ice shells in Asahikawa', Cold Regions Science and Technology, 11, 1985, 155-170.

[5] Kokawa T. and Murakami K., 'Challenge to 20 m span ice dome, Shells', Membranes and Space Frames, Proceeding IASS Symposium, Osaka, Vol.1, 1986, 297-304.

[6] Timoshenko, S.P. and Woinoesky-Krieger S., 'Theory of Plates and Shells', McGraw-Hill, London, 2nd ed., pp. 429-465, 1959.

[7] Kokawa T., 'Experimental study on creep buckling collapse of ice domes with 60 cm span (in Japanese)', Japan NCTAM, 33:151-152, 1983.

[8] Hirasawa I. and Kokawa T., 'On the creep behaviours of ice domes with 2 m (in Japanese)', Bull. Hokkaido Tokai Univ., 5:7-15, 1984.

[9] Kokawa T., 'Axisymetric creep buckling analysis of ice domes (In Japanese)', Bull. Hokkaido Tokai Univ., 5:17-24, 1984.

[10]Kokawa T., 'Construction and creep test of 15 m span ice dome', Proceeding of IAHR Ice Symposium 1988 Sapporo, 390-399.

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