ICE SHELL—TRANSITORY STRUCTURE IN WINTER

Tsutomu Kokawa
Cultural Institute of Northern Region, Hokkaido Tokai University
Asahikawa, Japan

1. INTRODUCTION

Snow and cold facilitate the application of an ice shell, which provides a quite unique built environment in snowy and cold regions. The ice shell is thin, and its structural material is ice. It is a new type of ice structures based on the modern structural engineering and it can cover a larger area compared to the classical snow-ice structures such as "Kamakura" or "Igloo". It provides an efficient architectural solution to certain problems in the snowy and cold regions during winter.

As described in a previous paper [1, 5], 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. Concerning to the structural safety and the construction technique, the theoretical and experimental studies had been carried out [1-7]. On the other side, concerning to the application of ice shell, 10-m span small ice domes had been practically used for a variety of temporary shelters such as a winter storage of vegetables, a factory house for making Japanese "sake" and a working space at the basement-area for Japan Observatory in the South-Pole [8].

The results of these studies provided the opportunity never experienced before to construct ice shells for an architectural space in Tomamu, Hokkaido since 1997. Many ice shells have been used as leisure spaces for visitor about 3 months in each winter and these have created a fantastic, beautiful space providing quite a unique built environment in winter [9]. Taking its architectural safety into consideration, the size of these shells is limited up to 15-m span for the time being. However, extensively interpreting the results in the past, a large ice shell with spans from 20 m to 30 m might be possible to use as an architectural structure. But, the actual proof test of the large ice shell had not been experienced before except the field experiment of 20-m span ice dome in 1985. Because of the lack of the actual experience so far, the confidence of its structural reliability to use for architectural facility is not enough. Therefore, toward the reliability of its structural safety and improvement of the construction technique, two field studies on a 20-m span ice dome with 6.5 m in height have been carried out at the same site of Tomamu in the year 1999 and 2000. These test-domes had shown a high structural efficiency compared with the first test-dome constructed in 1985 that had geometrical and material imperfections because of unskilled snow blowing operation.

This paper describes 1) construction method and structural safety of the ice shell, 2) recent architectural applications in Tomamu including a large free-shape ice shell and 3) field test of 20-m span ice dome in the year 2000.

2. CONSTRUCTION METHOD

2.1 Outline

"Kamakura" or "Igloo" is well known as a classical snow-ice structure, but it seems that these structure 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, and constructed by scooping out the snow from a small snow mountain. "Igloo" is a snow house for Inuit and 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 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 snowplow 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.

2.2 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 equilibrium to 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, bring not only the improvement of structural efficiency but also the geometrical beauty at the inside surface.

2.3 Snow Blowing and Water Spraying

In order to produce quickly a high quality of ice on the membrane, some special devices are needed. Snow is blown onto the membrane by a rotary snowplow 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 [6]. 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 attain 1 cm thickness. When the ice thickness reaches a certain value, 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 is light 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.

3. STRUCTURAL SAFETY

The strength of an ice shell is sufficient for some given loads over a short period [1]. However, as the snow-ice creeps, it is important to investigate the creep behavior of an ice shell which will experience loads for a long time. So, experiments on ice domes with 60-cm [2], 2-m [3], 5-m [5] spans under long-term loading, and the ax symmetric creep buckling analysis of ice domes [4], were conducted together with the beginning of investigations on the structural safety. Experimental creep tests of 10-m [5], 15-m [7] and 20-m [6] span model, which were constructed based on the prescribed method, were carried out carefully. The important result of these tests confirmed that the ice shells slowly produce a large creep deformation before the collapse. It indicates also that the collapse does not occur abruptly, and that is enough time to predict the danger of the collapse. This ductile behavior makes the use of ice shells possible for architectural structures.

4. RECENT APPLICATION

Based on the prescribed investigations, and because of both the easy construction technique and the high durability, following structures have been constructed over the past decade; 10-m span small ice domes have been practically used for a variety of temporary shelters such as a winter storage of vegetables, a factory house for

Fig.1 Ice Shells in Tomamu (1998-1999 winter)

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. This experience provided the opportunity to construct since 1997 ice shells for an architectural space in Tomamu as seen in Fig.1. The design and construction processes of a large free-shape ice shell, which was never done before, are described in the pictures following.

4.1 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 "2.2 Feature of Pneumatic Form". Thus 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.2 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

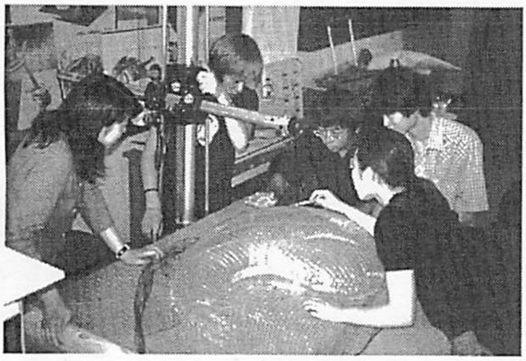

Fig.2 Measuring geometry 1/20 scaled model

Fig.3 Formwork for free-shape shell

Fig.4 Application of snow and water

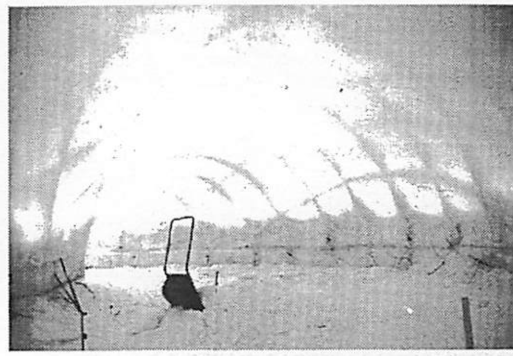

Fig.5 Inside after removing membrane

Fig.6 Inside for making ice-glass

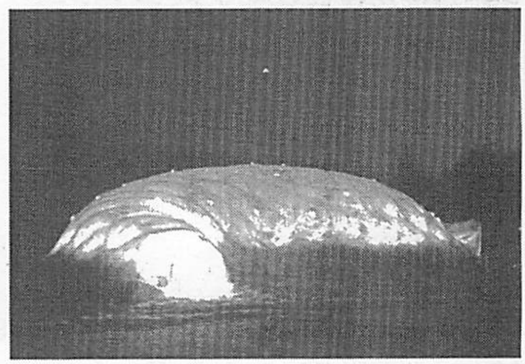

Fig.7 Exterior view

Finite Element Structural Analysis under gravity load, and it confirmed that the construction of the shell would be possible because the maximum compression stress was less than 9.8 N/cm^2. Fig.3 shows the full-scaled pneumatic formwork at the site. The maximum height has about 4.5 m. The formwork consists of a P.V.C. membrane and 10 mm diameter Polypropylene ropes which are laid orthogonal on the plane projection. Fig.4 shows the snow being blown by a rotary snowplow and tap water sprayed by an 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 air temperatures 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 method. The application of snow and water are repeated until 15 cm thickness is attained on average. The pneumatic formwork is deflated after that, producing a beautiful half-transparent internal space covered by a thin-curved wall with rib stiffeners, as shown in Fig.5. The inside space was used as a manufacturing room where visitor can make an ice-glass from an ice block, as shown in Fig.6. Fig.7 shows the exterior view when illuminated from the inside. It is judged that the completed shell has a good quality of ice.

5. FIELD TEST OF 20-M SPAN ICE DOME

A large ice shell with spans from 20 m to 30 m might be possible to use as an architectural structure. However, the actual proof test of the large ice shell had not been experienced before except the field experiment of 20-m span ice dome in 1985 [6]. Because of the lack of the actual experience so far, the confidence of its structural reliability to use for architectural facility is not enough. Therefore, toward the reliability of its structural safety and improvement of the construction technique, two field studies on a 20-m span ice dome with 6.5 m in height have been carried out at the same site of Tomamu in the year 1999 and 2000. These test-domes had shown a high structural efficiency compared with the first test-dome constructed in 1985 that had geometrical and material imperfections because of unskilled snow blowing operation. Here describes the construction and creep test of the year 2000' test-dome, and concludes, that the realization of 20-m span ice dome is possible to use as an architectural structure during winter in Hokkaido.

The construction process is briefly described as follows. After the completion of the snow-ice foundation that had about 17 m in inner diameter, 90 cm in depth and 1 m in width, a P.V.C. membrane bag covered by a net, was inflated as shown in Fig.8. Then, the milled snow was carefully blown onto the membrane by a rotary snowplow with the maximum throwing distance of 22 m, and tap water was continuously sprayed on the snow by 6 adjustable nozzles with the maximum spraying distance of 15 m and the total spraying amount of 60 litter/minute. Fig.9 shows the outside air temperature during the application of snow and water.

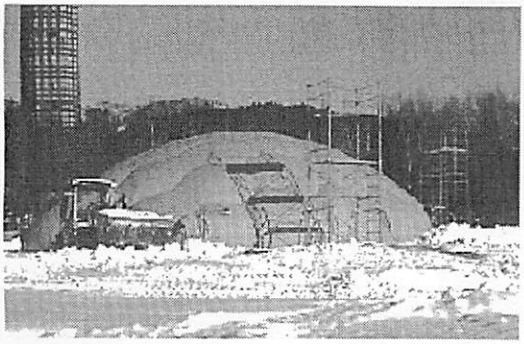

Fig.8 Air-inflated membrane as formwork

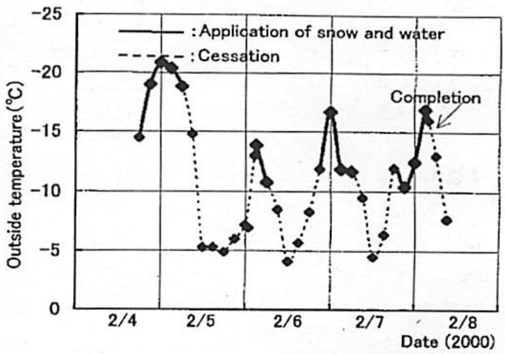

Fig.9 Outside temperature under construction

The completed dome was assumed to have 1040 cm radius of curvature and 1720 cm base diameter based upon the measurement of the central height and the inner diameter at the base. Fig.10 shows the shell thickness at the major points, and the distribution was fairly scattered because the frozen Styrofoam sticks with scale were not useful for reading the shell thickness under construction. The designed shell thickness was 15 cm at the top, 17.5 cm at the middle part and 20 cm at the bottom, but the result showed 12.5 cm, 17.9 cm and 18.4 cm in average respectively. The thickness was comparatively thin at the bottom because of the steep slope. It took 2 hours to get 1 cm thickness in this construction because it needed 36 hours in total to attain the average thickness 17.9 cm as shown in Fig.9 and 10.

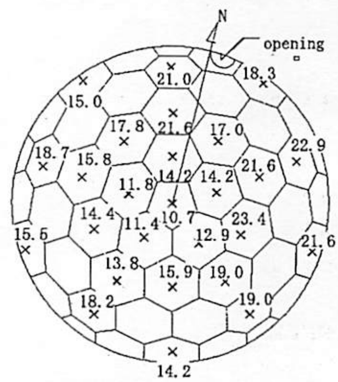

Fig.10 Ice thickness (cm)

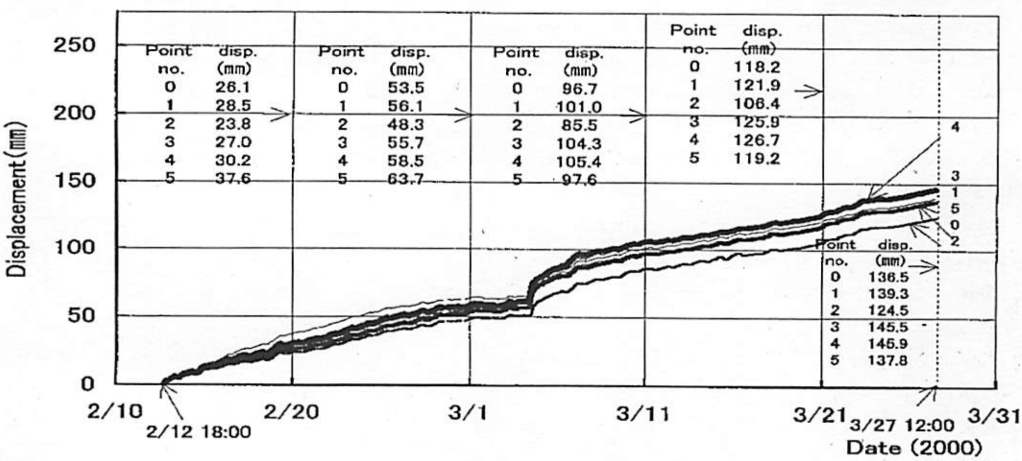

Fig.11 $\delta_{0\sim5}$-time curves

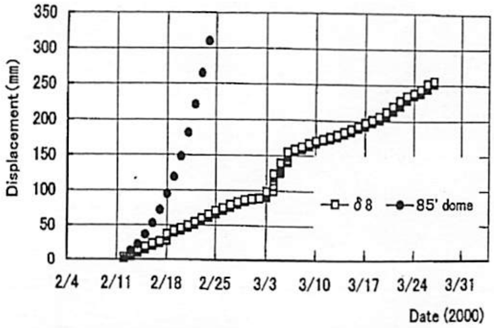

Fig.12 Comparison between 00' and 85' dome

Fig.13 Large deformation onset collapse

21 vertical displacements and 5 temperatures were automatically measured from February 12th to March 27th. Fig.11 shows the central points of displacement-time curves during the whole period. In this Fig., the most noteworthy point is that the deformation from March 4th to 6th dramatically increased because ice temperatures constantly kept 0℃ in this period because of warm air and strong sunlight at the beginning of spring. However, other periods, the structural behavior was stationary and the central points of average creep displacement was 2.5~3.0 mm/day. Fig.12 shows the 2000' dome had a high structural efficiency compared with the 1985' dome that had geometrical and material imperfections [6]. After the automatic measurement, the structural behavior was observed by eye up to the collapse. The collapse occurred on April 4th after a large deformation as shown in Fig.13.

6. CONCLUSION

Snow has been normally considered to be a nuisance in the snowy and cold regions. However, as shown in this paper, snow becomes a useful structural material for the construction of the ice shell, which creates a fantastic, beautiful space providing quite a unique built environment in winter. Ice shell provides an efficient architectural solution to certain problems in the snowy and cold regions. Therefore, snow may be said to be a valuable present from the sky.

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