Building Techniques for Ice Shell as Temporary Structure

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Summary

Shell structures in general are constructed of such varied materials as steel, aluminum, plastics, wood and reinforced concrete. In addition to these materials, ice can be used as structural material for shell structure. Ice shells, which are thin curved-plate structures made of ice, have been used as temporary winter structures since 1980s in inland Hokkaido with sufficient snow and low temperature. The construction method of blowing snow and spraying water onto the pneumatic formwork consisting of a 2-dimensional membrane bag and a reticulated cover rope has constructional rationality. The ice structure has also high structural efficiency as a shell. This paper comprehensively describes the technical points on the construction, the structural design and the maintenance of the ice shell as temporary structure.

Keywords: *Ice shell; temporary structure; construction technique; structural design; maintenance; creep*

1. Recent Applications to Winter Architecture

At IASS Dortmund symposium in 1984, the author presented internationally a first paper on an ice shell [2]. Almost 30 years since then, nowadays, as shown in table 1, the shells are being practically used inland Hokkaido with sufficient snow and low temperature for a variety of temporary structures such as a winter storage of vegetables, a factory house for making Japanese "sake", an indoor space for an ice fishing on a frozen lake and event facilities for winter festival etc. [1][10]. As the typical example of the applications, since 1997 in Tomamu shown in Figure 1, many ice shells are being used each winter for about 75 days as leisure-recreational facilities in a ski resort [1]. The shell creates a beautiful space in the environment from the translucent thin plate and the unique curved surface shape. The interior space has a translucent atmosphere with full of natural light in daytime, and the exterior looks like gigantic illuminators in the dark at night.

Table1 : Meteorological Data(1981-2010)
(http://www.jma.go.jp/jma/index.html) and Usage

Construct-ion site	January~February		Usage (year)
	Average air temp.(C^{o})	Precipi-tation (mm)	
Tomamu	-9.8	92.9	Leisure-recreation (1997~)
Asahikawa	-7.0	120.9	Sake factory-storage (1989~), Winter festival (2008~), Ice pantheon project (2009~)
Lake Syumarinai	-9.4	253.8	Ice fishing (2004~2006)
Nakagawa	-8.0	147.5	Work shop(2003~2005)

Fig.1 Ice Shells in Tomamu(2008-2009 winter)

2. Construction Technique

2.1 Outline

”Kamakura” and igloo are well known classic snow structures. A ”Kamakura” is a Japanese traditional snow hut where children play house during the New Year holidays, and is formed by scooping out snow from a small mound of snow. An igloo is a snow hut built by arranging snow blocks hemispherically. However these structures are generally very small in size.

Contrast to these traditional construction methods for small structures, in 1980s, the author developed a construction method for a large ice shell [2]. The method is technically simple, mechanically reasonable and economical as stated below and shown in Fig. 2.

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

(2) Covering the membrane with a thin snow-ice layer (less than 1cm) by blowing milled snow with a rotary snow blower, spraying water and letting it freeze naturally at temperatures below -10℃.

(3) Repeating the application of snow and water until the desired shell thickness is reached, then removing the bag and ropes for reuse.

2.2 Pneumatic Formwork

2.2.1 Features

Economical formwork is very important to realize shell structure as seen in the field of reinforced concrete shells [4]. A special air-inflated formwork is used for the ice shell construction [2].

The air-inflated formwork consists of a 2-dimensional membrane bag and reticulated cover ropes. The membrane does not require 3-dimensional cutting as the ropes form the general shape of the formwork. This makes the membrane easy to fabricate even when the shape of the 3-dimensional formwork is complicated. The ropes play an important role in forming the shape of the formwork. The tension in the ropes is in equilibrium with the inside air pressure. Many different shapes can be made from the same membrane bag by changing the length and reticular pattern of the ropes. Free-shaped formworks with various forms of non-axisymmetric surface can be prepared easily in combination with arbitrarily shaped 2-dimensional membrane bag and appropriate

(a) 2-dimensional membrane bag

(b) Air inflated membrane

(c) Application of snow and water

(d) Removing membrane

Fig. 2:Construction sequences of 15m ice dome constructed by students of Tokai University [3]

reticulated cover ropes. Because a uniform pressure decides automatically these shapes, a compressive membrane force works mainly in the completed ice shell. So, this structure makes the best use of the ice as the structural material, which has relatively high compressive strength. Furthermore, the general shape of the formwork obtained automatically by this method regularly consists of a number of bulges surrounded by cover ropes. A family of reinforced ribs with large sectional areas along the ropes would improve the structural performance as a ribbed ice shell. And then the ice shell also gives the geometrical beauty at the inner surface.

In addition to the inflation of the pneumatic formwork in a short time, so that it can also be kept at a constant air pressure in the construction process, an easily available portable air-blower with a plenty of airflow and a low air pressure (300 ~ 500Pa) is used. The rigidity of the pneumatic formwork is relatively high due to the effectiveness of holding down the membrane bag by the cover ropes although low air pressure. Many ice shells can be economicaly produced by using the formwork repeatedly.

2.2.2 Examples

Figure 3 shows examples of the formworks used for ice shell construction in the past. Fig.3 (a),(b) and (c) have circular membrane bags, but different reticular pattern of cover ropes. Figure 3 (d) shows the formwork for a free-shaped ice shell [7]. While PVC is normally used as the material for the membrane bag, a large commercially available blue-sheet made of polyethylene is also used for the bag because it is inexpensive and resist to low temperature. 10~16Φ PP (polypropylene) rope is used for the cover ropes because of cost performance and good mechanical property.

(a) Circular membrane bag (15m diameter)
+ Grid pattern [12]

(b) Circular membrane bag (20m diameter) +
Hexagonal and Pentagonal pattern from Geodesic [5]

(c) Circular membrane bag (30m diameter)
+ Triangular pattern from Geodesic division [6]

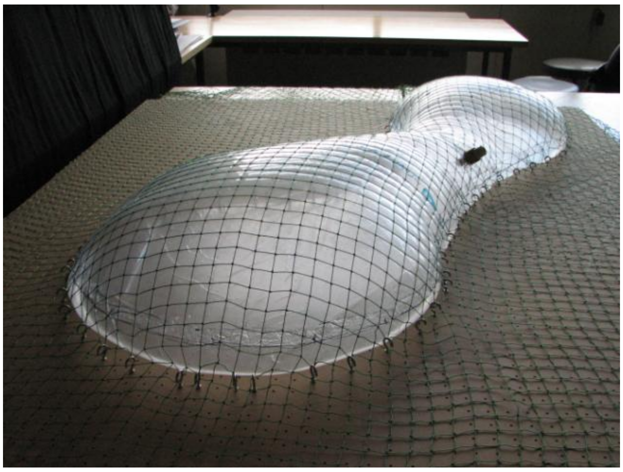
(d) Non-circular membrane bag
+ Grid pattern [7]

Fig.3 Shapes of formwork from (2-dimensional membrane bag + reticulated cover ropes)

2.2.3 Free-shaped Models

A free-shaped formwork is easy to make in combination with 2-dimensional membrane bag and reticular net. As examples of the formworks for free-shaped shells, Figure 4 shows models consisting of arbitrary 2-D membrane bag and uniform mesh nets with square meshes.

(a) Model 1



(b) Model 2

Fig.4 (Non-circular 2-dimensional membrane bag + square mesh) models

2.3 Blowing Snow and Spraying Water

In order to produce quickly a high quality of ice on the pneumatic formwork, some special devices are needed. 0.4~0.5 g/cm^3 high density of snow should be blown onto the formwork by a rotary snow blower and water sprayed on the snow by an adjustable nozzle. The snow+water mixture formed on it is frozen hard some time later under the air temperature -10℃ below. It is necessary during each blowing to keep the snow depth less than about 1 cm thickness. Otherwise, when water is sprayed, only the upper layer of the snow will change to ice and the other layer might remain snow. This condition is called ‘Sandwich-Snow’ which leads to causes of material and/or geometrical imperfections in the completed ice shell [9]. The snow absorbs the sprayed water and keeps some of it from running down the sides. Since snow is a form of ice, it is natural that snow+water mixture freezes faster than water alone; therefore, it is possible to complete a dome in less time and at higher temperatures by using snow in the construction. Experience shows that the thickness of the ice increases by about 1 cm every 90 minutes when the outside temperature is approximately –10^{o}C, and its density is in the range of 0.83 to 0.88 g/cm^3. The thin snow layer must be saturated and the amount of water needed varies with the air temperature The amount of the total

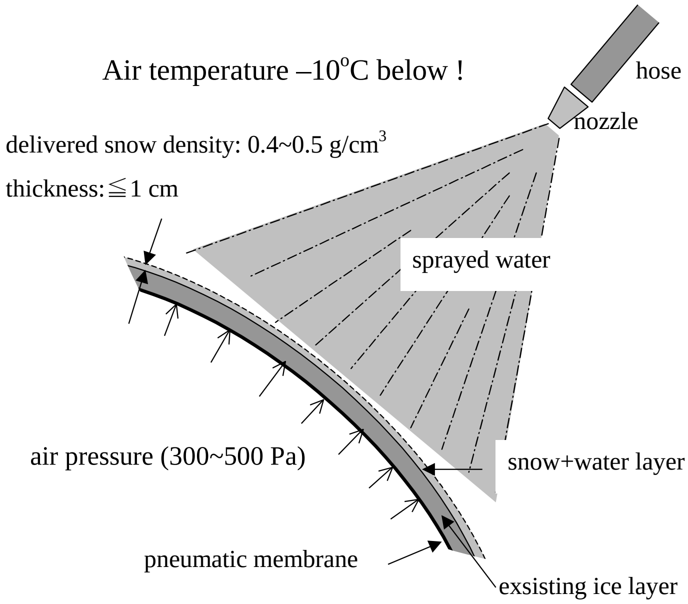


Fig. 3 Application of snow and water

delivered water, W_v(l/min.) is given by Eq.(1) derived from construction experiences and a study on freezing of (snow+water) to (ice) [8].

$$W_v(l/\min.) = \frac{(38.2 - 5.42T_a)A_d}{500} \tag{1}$$

Where T_a is outside air temperature in ^{o}C and A_d is surface area of ice shell in m^2.
For example, in case of a 15m ice dome which uses 15m diameter of circular membrane bag for pneumatic formwork, the A_d is about 210m^2. When T_a=−10^{o}C, W_v becomes 38.8 *l*/min and W_v becomes 61.6 *l*/min for T_a=−20^{o}C

When the ice thickness reaches a few centimeters, the shell itself can support the weight of new snow+water layer instead of the air-inflated formwork. Therefore, 300~500Pa low air pressure in the membrane bag is enough as pneumatic formwork for the ice shell construction. And then consequently the manufacturing cost for the formwork is not expensive. The application of snow and water are repeated up to the designed shell thickness, which is normally about 1/100th of the span.

A major big problem of this method is described as follows. If there is a snowfall of more than 10cm on a very thin ice shell at the beginning of the construction process, workers have to remove the snow just before the application of snow and water in order to avoid 'Sandwich-Snow' mentioned above. However, they cannot go up on the dome as it might be broken by their own load, if the ice thickness on the apex at the moment is thinner than 6cm for 15m base diameter or less and 7cm over 15m up to 30m base diameter [11]. So far, the author has not found yet a smart solution to this problem. Exaggeratedly speaking, the success of the ice shell construction is strongly depend on the weather condition at the beginning stage of snow blowing and water spraying up to the determined ice thickness mentioned above.

2.4 Positional Relationships between Foundation Ring and Formwork

A snow-ice foundation ring is constructed using plenty of snow in addition to water before inflation of the formwork. As shown in Fig.5, the end rope embedded in the ring is one touch connected by shackle to the cover ropes. The diameter of rope has to be selected so that the tension force in the ropes computed due to its curvature and a distributed load from the membrane bag is smaller than the tension strength of rope. If the anchor of the end rope is not enough, the formwork becomes unstable and then the produced thin ice at the beginning stage of the construction process breaks. Therefore the position of the anchor in the ring and its sectional area should be adequately designed predicting the creep stability against the drawing force from the cover rope. As the other role of the foundation ring, it should be smoothly connected to lower part of the shell. If the lower part of formwork does not touch to the inner side of the ring, it will take a very long time to fill up the clearance with blown snow. Therefore, the positional relationship between the foundation ring and the pneumatic membrane bag should be carefully

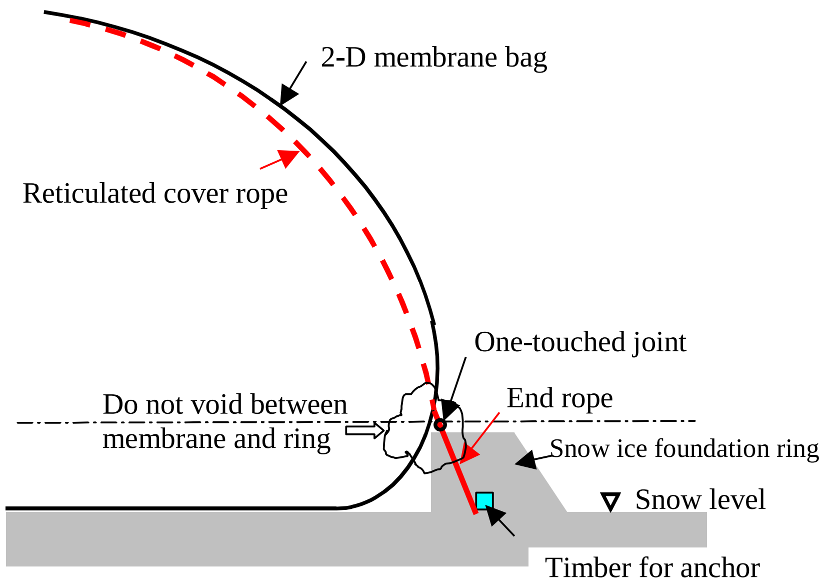


Fig. 5 Positional Relationships between Foundation Ring and Formwork

decided. For instance, in case of spherical ice dome which uses circular membrane bag, if the diameter of the membrane is 10m, 15m, 20m, 25m and 30m, (the inner diameter and its height) of the ring are normally (8.6m and 45cm), (12.6m and 70cm), (17.6m and 90cm), (21.6m and 120cm) and (25.2m and 150cm), respectively. Furthermore, the width of the foundation ring has to be adequately designed taking into consideration on working space for spraying water on the ring and drawing force for the anchor. If the size of ice dome is large, the ring requires a plenty of snow and a heavy construction machine such as power shovel or a large rotary snow blower will be used for the construction of snow-ice foundation ring.

3. Structural Safety

3.1 Structural Design

According to the past construction experiences, the ice shell is very easy to creep even when the working stress is small. Large creep deformations are fatal to the structures and, therefore, the creep deformation should be taken into consideration. However, much have not been known about the creep phenomenon and so the following attentions are paid in order to get sufficient structural safety against creep behavior;

a. Ice shell must be supported rigidly along a snow-ice foundation ring.

b. Periphery of openings should be stiffened.

c. The maximum membrane stress due to its own weight has to be less than 10 N/cm^2, which corresponds to about 1/40 to 1/50 of the uniaxial compressive strength of ice.

3.2 Creep in Spherical Ice Dome

The ice temperature of the domes is between 0 ^{o}C and –5 ^{o}C according to the past field experiments. The ice in this range creeps easily, and the deflection of the structure increases with time, even if there is no increase in working stress. Therefore, it is necessary to prepare a rational structural design method considering not only a stress regulation but also deformation or strain rules in relation to time. From the results of the past field experiments of ice domes spanning 10 to 30 meters, the following are pointed out in relation to the deflection-time curves, including the

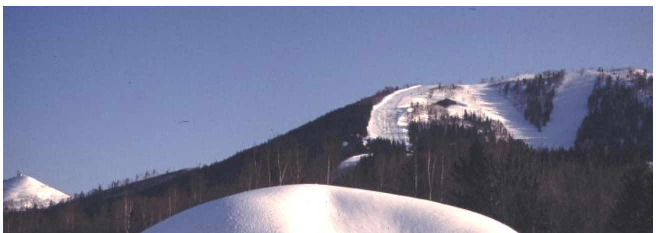


Fig. 6 Large creep deformation before collapse

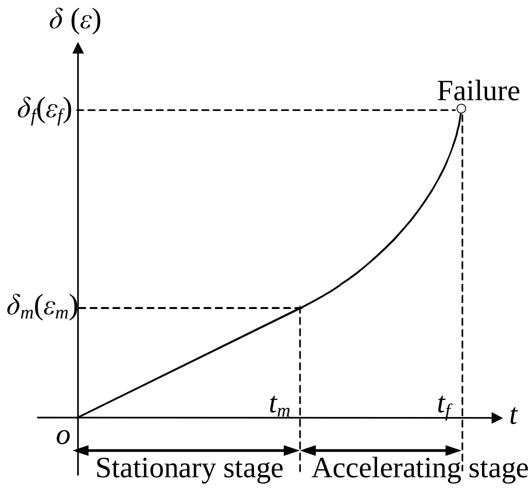


Fig. 7 Model of deflection(strain)-time

structural behavior up to the failure:

1. the creep deflection has a linear function of time at the beginning
2. the deflection rate increases with time until collapse
3. collapse occurs after the daily average temperature above freezing lasts 2 to 3 days

4. when the deterioration of the ice is not too advanced, a large deformation should be visible before the collapse as shown in Fig.6.

The simplified deflection-time curve is shown in Fig. 7. That is, the creep deflection-time curve is approximately given by connecting two lines; the first is secondary stage where the deflection has a linear function of time, and the second is accelerating stage where the deflection rate increases with time up to the point of failure. This curve coincides with a strain-time curve from which the elastic response and the primary stage in the uniaxial creep test under constant stress and temperature are omitted. The quantitative evaluation of $\delta_m(\varepsilon_m)$ and $\delta_f(\varepsilon_f)$, which is indispensable in establishing an allowable-strain design method, is left for future study.

The author proposed a simplified formula for computing the creep deflection during the stationary stage based on the data [13]. The derivation of the formula is as follows: assuming ice to be a Newtonian fluid and using the invariant theory for the creep material and the membrane theory for a thin shell, the vertical displacement rate at the top, $\dot{\delta}_{vo}$ is analytically given by Eq. (2).

$$\dot{\delta}_{v0} = \frac{qr^2}{\eta h}\left\{(1-\cos^2\alpha)+1.5\log(\frac{2}{1+\cos\alpha})\right\} \qquad \text{..... ....(2)}$$

Where η is viscosity of ice, r is radius of spherical dome, h is ice thickness, α is half-open angle of spherical dome and q is self-weight per unit area. The evaluation of the viscosity of the ice, η is based on the creep deflection data obtained from the field experiments and the average viscosity is computed to be approximately 3500 kgf·cm^{-2}·day. The simplified formula satisfactorily predicts the creep deformation of spherical ice domes when the ice temperature is in the range of 0 ^{o}C to −5 ^{o}C. Referring to Eq.(2), it is easy to calculate $\dot{\delta}_{vo}$ because it is a function of r (cm), h (cm), α(^{o}) and q(kgf/cm^2). For example, if the dome has a 40m base diameter and a height of 12.35m, $\dot{\delta}_{vo}$ is calculated at 15.5 mm/day(=1.55 cm/day) under dead load, substituting r=22.37m (=2237cm), α=63.4^o, $q/h=\rho$ =0.85 g/cm^3 (=0.85·10^{-3}kg/cm^3) into Eq.(2), where ρ is ice density.

3.3 Maintenance

Meteorological condition influences the deterioration of the ice in the shell. Impermanent plus-outside air temperature and rainfall promote the phenomenon, and especially the sunlight attacks dramatically the ice at the south side of the ice shell though low temperature below 0. The ice does not immediately lose the strength and rigidity under these weather conditions because of its latent heat, therefore the shell can keep the stability for a while. However, the ice melts a bit by bit every these weather conditions occur. This melting causes the deterioration of the ice. As the deteriorated ice becomes brittle because of weak bonding forces between the ice grains, the short term strength of the shell degrades and the failure may take place without a large creep deformation. In order to slow down the speed of the deteioration and then make the life span of the ice shell longer, a very low density snow is blown onto the ice shell by a snow blower because the snow has a high performance in the thermal insulation. On the other side, in case of leisure or event facilities, the ice is exposed for enjoining the lighting presentation. Although this is not good for the maintenance of the shell, spraying water onto the shell should be carried out after the presentation in order to recover the quality of the ice.

A large creep deformation, a russy melting of the ice, ice thickness less than 6 cm, and a wheather condition such as lasting strong radiation and plus air temperature are current judging methods for closing to use the shell.

4. Ending Remarks

Ice shells have been used in winter as temporary structures since 1980s in inland Hokkaido with

sufficient snow and low temperature. The shell can be constructed if there is a spraying nozzle, a snow blower, an air blower, a 2-dimensional membrane bag, a reticular cover rope, snow and water. The shell creates a beautiful space in the environment from the translucent thin plate and the unique curved surface shape. The interior space has a translucent atmosphere with full of natural light in daytime, and the exterior looks like a gigantic illuminator in the dark at night. Also, the shell is environmentally compatible because it simply returns to the earth as water in spring.
This paper described conprehensively the current techniques from constructional and structural engineering aspects such as construction, building design, structural safety and maintenance which led to the realization of the ice shell as temporary structure.

The ice shell has a possibility to become a useful structure common in not only inland Hokkaido but also the severe cold regions all over the world such as Canada, Alaska, Northeast China, North Scandinavian, Russia and the South Pole. The author would like to hope for the new development of the usage and the expansion of application in those areas. The ice shell, concept developed in Hokkaido, should be used in snowy and cold regions all over the world.

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