Ice Shell Construction in Hokkaido

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Summary

Ice shells, which are thin curved-plate structures made of ice, have been used as winter structures since 1980s in inland Hokkaido with sufficient snow and low temperature. As the typical example of the applications, since 1997 in Tomamu, many ice shells are being used each winter for about 3 months as leisure-recreational facilities after skiing. 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.

The construction method of blowing snow and spraying water onto the pneumatic formwork consisting of a 2-dimensional membrane bag and a reticulated rope cover has constructional rationality. The ice structure has also high structural efficiency as a shell.

This paper describes the comprehensive developments of ice shell construction in Hokkaido, along the following topics.

1) Constructional and structural engineering
2) Applications in Hokkaido
3) Field experiments of huge ice domes
4) Creep in ice dome
5) Ice Pantheon Project towards realization of 40m ice dome

Keywords

Ice shell, construction technique, structural design, applications, huge ice domes, creep, ice pantheon project

1. Introduction

The author developed the ice shell construction at the beginning of 1980s [1]. The construction method of blowing snow and spraying water onto the pneumatic formwork consisting of a 2-dimensional membrane bag and a reticulated rope cover has constructional rationality. The ice structure has also high structural efficiency as a shell. The ice shells, which are thin curved-plate-structures made of ice, have been used as winter structures since 1980s in inland Hokkaido with sufficient snow and low temperature. 10~15m ice domes which use 10~15m diameter of circular membrane bags, have been especially used 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 an event hall for a winter festival etc. [2][3]. The ice dome was also used as a working space for Japanese research station in Antarctica [4]. As the typical example of the applications, since 1997 in Tomamu, many ice shells are being used each winter for about 3 months as leisure-recreational facilities after skiing. 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.

This paper describes the comprehensive developments of the ice shell construction in Hokkaido, along the following topics; 1) constructional and structural engineering, 2) applications to architectural structures, 3) field experiments on huge ice domes, 4) creep behaiour of ice dome and 5) Ice Pantheon Project towards realization of 40m ice dome.

2. Constructional and Structural Engineering

2.1 Construction method

"Kamakura" and igloo are well known classic snow-ice 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

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structures are generally very small in size.
Some attempts began to innovate methods for snow-ice dome construction in 1960s-1970s. Construction test on a snow dome with a 10m base diameter, was carried out by blowing milled snow over an inflatable hemisphere by a Peter miller [5]. Stanley and Glockner proposed a construction method of ice dome and carried out an experimental creep study on reinforced ice domes with a 2m base diameter produced by spraying water onto an inflatable membrane [6]. The same method was also used for ice structures in Europe [7][8]. However, these studies did not make a progress because the technical devices such as the inflatable membranes of formwork were not suitable and/or ice having appropriate mechanical quality was not formed on the membranes.
Since 1990s, a snow vault has been used in the northern parts of Scandinavian countries [15]. The snow vault is constructed by blowing snow on a high-rise arched wooden or metal mould and adding water or sea water directly into the snow shower while blowing [16]. The inside span is limited to 5m because the mould is sturdily heavy in order to support the weight of the blown snow during construction and the vault is subject to creep rapidly because of snow structure.
In1980s, a construction method for large ice shells was developed by the author [1]. The method is technically simple, mechanically reasonable and economical as stated below and shown in Fig. 1.
(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 (1cm) by blowing milled snow with a rotary snow blower, spraying water and letting it freeze naturally at temperatures below -10°C.
(3) Repeating the application of snow and water until the desired shell thickness is reached, then removing the bag and ropes for reuse.


(a) 2-dimensional membrane bag


(b) Air inflated membrane


(c) Application of snow and water


(d) Removing membrane

Fig. 1:Construction sequences of ice shell (IPP2010)[14]

The air-inflated formwork consists of a 2-D membrane bag and cover ropes. The membrane does not require 3-dimensional cutting because of the force control by cover ropes. This makes the fabrication of membrane very easy even when the shell form is complicated. The cover ropes play an important role in forming the shape of the inflated membrane. The tension in the ropes is in equilibrium with inside air pressure. Changing the length and geometric pattern of the cover ropes, various shapes can be made from the same membrane. The most important objective of construction work is to produce a high quality of ice quickly on the membrane. Referring to Fig. 2, special attentions should be paid on the following points for this purpose[9];

(a)Appropriate selection of snow blowers and water spray nozzles.

(b)Controlling the snow depth during each blowing work. The snow crushed with a snow blower is a type of sintering snow with density of 0.4~0.5 g/cm^3. The thickness of snow each blowing must be less than about 1cm. Otherwise, when water is sprayed, only the upper layer of the snow will change to ice and the other layer might remain snow. This leads to causes of material and/or geometrical imperfections.

(c)Appropriate combinations of snow-water mixture solidify more quickly than water alone, and the ice seems to be produced with much ductility under the air-temperature −10°C below. It normally takes 1.5 hours for snow-water mixture to attain 1cm thickness ice. When the thickness of ice shell exceeds a certain value, the shell itself can support the weight of new snow-water layer instead of the air-inflated formwork.

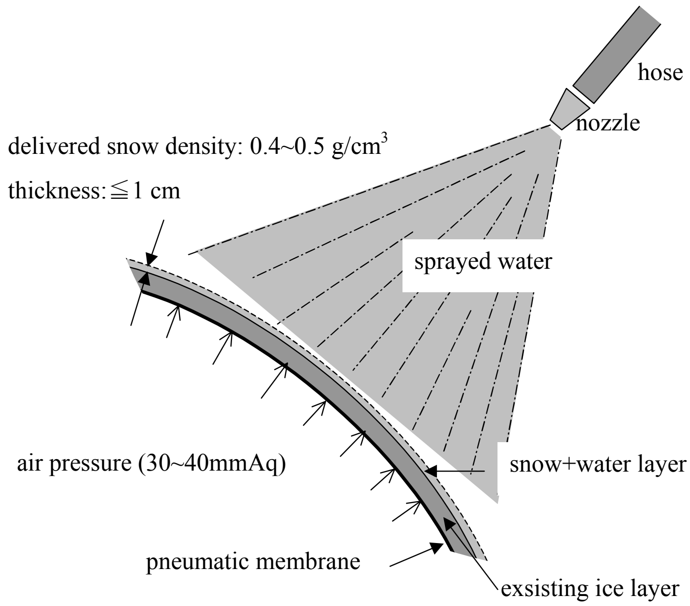


Fig. 2 Application of snow and water

Workers can go up on the ice dome under costruction in order to spray water there, if the ice thickness is 6cm for 15m base diameter or less, and 7cm over a 15m up to 30m base diameter [10].

(d)The amount of the total delivered water, W_v(l/min.) is given by Eq.(1) derived form construction experiences and a study on freezing of (snow+water) to (ice).

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

Where T_a is outside air temperature in °C and A_d is surface area of ice shell in m^2.

For example, in case of 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°C, W_v becomes 38.8 *l*/min and W_v becomes 61.6 *l*/min for T_a=−20°C.

2.2 Structural design

The ice shells are 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 author has proposed to pay following attentions 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.

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 1/50th of the uniaxial compressive strength of ice.

3. Applications to Architectural Structures

Sufficient snow and low temperature below -10 °C are necessary for the ice shell construction. Inland Hokkaido is suitable place to build the ice shells because of its natural environment shown in Table 1.

Table 1 Metrological data in construction place (http://www.data.kishou.go.jp/etrn/)

Construction Place(Usage)	Month	Air temperature(°C)			Precipitaion (mm)
		Avarage	Heighest	Lowest	
Tomamu (Leisure)	1	-10.3	-4.0	-18.2	51.7
	2	-9.8	-3.2	-18.3	35.3
Asahikawa (Sake Factory) (Winter Festival)	1	-7.8	-4.0	-12.6	74.1
	2	-7.2	-2.7	-12.6	51.5
Syumarinai (Ice Fishing)	1	-9.6	-5.2	-15.5	150.0
	2	-9.5	-4.3	-16.4	99.5

Many ice shells are beeing used every winter in inland Hokkaido as temoprary structures. Especially 10~15m ice domes have been used for a variety of temporary shelters 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, an event hall

(a) Ice Shells in Tomamu (2009-2010 winter)

(b) Ice glass workshop(Tomamu)

(c) Ice dome concert (Asahikawa winter festival)

(d) Sake factory (Asahikawa)

(e) Ice fishing (Lake-Syumarinai)

Fig. 3 Examples of applications

for a winter festival etc.[2][3]. And the ice dome was used for a working space in the basement-area for Japan Observatory in the South Pole[4]. As the typical example of the applications, since 1997 in Tomamu, many ice shells are being used each winter for about 3 months as leisure-recreational facilities after skiing. 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.

4.Field experiments on Huge Ice Domes

Taking architectural safety into prudent consideration, the size of practical shells had been limited to no more than 15m span. However, extensively interpreting the results of the past studies, a large ice shell with span between 20m and 30m would be possible to use as an architectural structure. And then, two field studies on a 20m ice dome (l7m base diameter and 6.5m height) were carried out at Tomamu in l999-2000 [11]. These test domes showed a high structural efficiency. Following the experiments with 20m ice domes, a field study on both the construction and creep test of a 30m ice dome (25m base diameter and 9.2m in height) was carried out at the same place during the winter of 2001 [12], assessing the possibility of its realization from the aspect of architectural engineering. Based on the results of these studies, it is concluded that the application of a 20~30 m ice dome for an architectural facility would be practicable.

(a) Creep test of 20m ice dome

(b) Consruction of 30m ice dome(Base diameter=25.0m, Height=9.2m)

Fig. 4 Field experiments of huge ice domes

5. Creep in Ice Dome

5.1 Large creep deformation of ice domes

According to the past field experiments, the ice temperature of the domes is between 0 °C and –5 °C. 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 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

Fig. 5 Large creep deformation before collapse

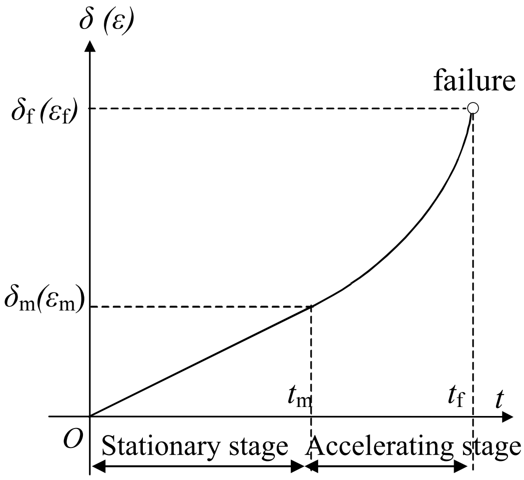


Fig. 6 Model of deflection(strain)-time curve

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. 5 [11].

The simplified deflection-time curve is shown in Fig. 6. 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.

5.2 Simplified formula for stationary creep deflection of spherical ice dome

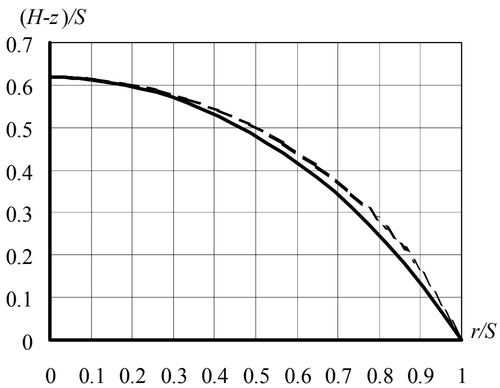
The author proposed a simplified formula for computing the creep deflection during the stationary stage based on the data [13]. The derivation of the formula is as follows: assuming ice to be a Newtonian fluid and using the invariant theory for the creep material and the membrane theory for a thin shell,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

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

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 °C to −5 °C. Referring to Eq.(2), it is easy to calculate $\dot{\delta}_{vo}$ because it is a function of r (cm), h (cm), α(°) and q(kgf/cm²). 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°, q/h= ρ =0.85 g/cm³ (=0.85·10⁻³kg/cm³) into Eq.(2), where ρ is ice density.

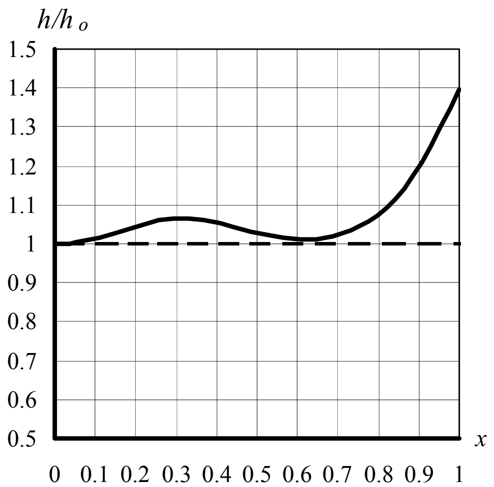
6. Ice Pantheon Project towards Realization of 40m Ice Dome

According to the shape and the creep deflection analysis of an axisymmetric ice dome, a non-spherical ice dome improves significantly the structural performance compared to the conventional type of spherical dome [14]. The analysis of an axisymmetric ice dome is based on the followings: membrane theory for a thin shell and invariant theory for the ice obeyed Glen's law during the secondary creep stage. In addition to the numerical results of the analysis, the past construction experiences and the field experiments of 20~30m ice domes would support the realization of a huge ice dome spanning 40 meters never existed before, which has almost



(a) Meridian curve of dome

:IP (Ice Pantheon Dome)
:S (Spherical Dome)

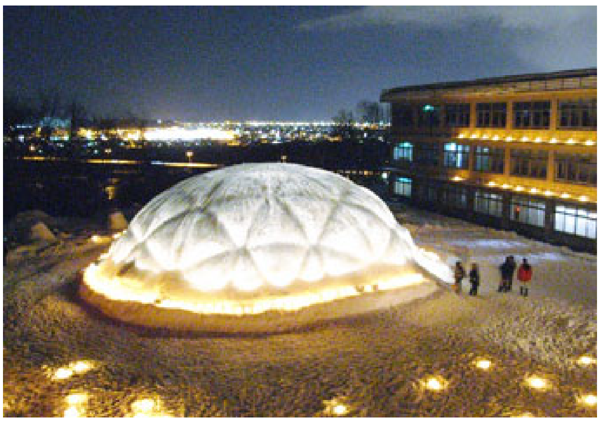


(b) Distribution of thickness

Fig. 7 Comparison between IP dome and S dome

(a) IPP2009(Base diameter=8.6m, Height=3.0m)

(b) IPP2010(Base diamete=12.6m, Height=5.0m)



(c) IPP2011(Base diameter=16.0m, Height=6.3m)

Fig. 8 IPP 2009-2011

same size as Pantheon in Rome well known as one of the biggest classical stone dome. The ice dome is easier to construct than the stone dome and the strength/density of the ice is almost same as that of stone in short term loading, so it could be possible for students as amateur to construct a 40m ice dome if they gradually experience the construction from small domes. Towards the realization of the ice dome, so called 'Ice Pantheon', the students started to go on an exciting, thrilling and wonderful voyage under the technical guidance by the author. In winter of 2009, as the first step toward this end, a small size of 10m span ice dome was constructed. In winter of 2010, a non-spherical 15m ice dome was constructed by them and used as event architecture. And then in this winter the students tryed to construct a non-spherical 20m ice dome shown in Fig.8, which was not practically used before, although three 20m ice domes were constructed for creep experiments in the past.

7. Concluding Remarks

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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