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ICE SHELL – CONTEMPORARY "*KAMAKURA*"

Tsutomu Kokawa[1], Koji Watanabe[1], Tohru Watanabe[2]

[1] *School of Design, Tokai University, Asahikawa, Japan*
[2] *Hoshino Resort Corporation, Tomamu, Japan*

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Abstract: Ice and/or snow can be used as a structural material for a temporary building in snowy and cold regions. Ice shells, which are thin curved-plate structures made of ice, were developed in 1980s by one of the authors as an architectural technique for creating a unique built environment in winter with sufficient snow and low temperature. It may be considered contemporary '*Kamakura*' which is well known as a Japanese traditional snow hut. 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 construction rationality. The ice structure has also high structural performance as a shell. The shell creates a beautiful space in the environment because of the translucent thin plate and the unique curved surface shape. The ice shells are being practically used as temporary structures for winter activity in Hokkaido of Japan.

1. Introduction

Architectural buildings in general are constructed of such varied materials as steel, aluminum, timber and reinforced concrete. In addition to these industrial materials, some natural materials are still being used as structural material for architecture. Especially there are many earth buildings constructed of mud brick, rammed earth, cob, compressed earth block or other methods of earthen construction in Africa, Middle East and Asia which belong to Dry climates zone [1]. Compared to many examples of earth buildings, there are a few examples of snow and/or ice constructions for winter architecture in snowy and cold regions.

Japan which is located at the most east side of the Silk Road, has the long land in the direction of about 3000km from Hokkaido in the northeast to Okinawa in the southwest. Therefore, the climate varies from cool temperate in Hokkaido to subtropical in Okinawa. Hokkaido and Tohoku region, which are located at the northern part of Japan have cold and snowy climate during winter, and snow and/or ice are used as structural material for creating rich living spaces in winter. Referring to Fig.1, in Tohoku, a snow hut called "*Kamakura*" where children play house during the New Year holidays, is well known as snow architecture since old days. The snow hut is formed by scooping out snow from a small mound of natural wet snow. It is a fantastic dome, however it is generally very small in size because its structural material is snow which mechanical property is very low. On the other hand, the ice shell, which is a thin curved plate-structure made of ice, can cover a much wider space than "*kamakura*". The ice shell which is suggested as an architectural technique in snowy and cold regions during winter, can be used for creating a unique built environment. It may be considered to be a contemporary "*Kamakura*". It is a new type of ice structure based on modern structural engineering. 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 construction rationality [2]. The ice structure has also high structural performance as a shell. During almost 30 years since proposing the construction method, the shells have been 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 [3]. 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.

Fig. 1: "*Kamakura*"
http://pics.livedoor.com/u/kamebugofukuten/4584147

This paper comprehensively describes the construction method of the ice shell and two examples of the current applications to winter architectural structures in Hokkaido.

2. Construction method

2.1 Examples of snow buildings

There exist a few snow buildings which inside space are practically used for architectural purpose. ”*Kamakura*” and igloo are well known classic snow domes. 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. These structures are easy to build, however the size is generally very small.

Since 1990s, a snow vault has been used in the northern parts of Scandinavian countries [4]. 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 [5]. 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 using snow as structural material.

2.2 Outline of ice shell construction method

In1980s, a construction method for large ice shells was developed by one of the authors [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 thickness) by blowing milled snow with a rotary snow blower, spraying water and letting it freeze naturally at air 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

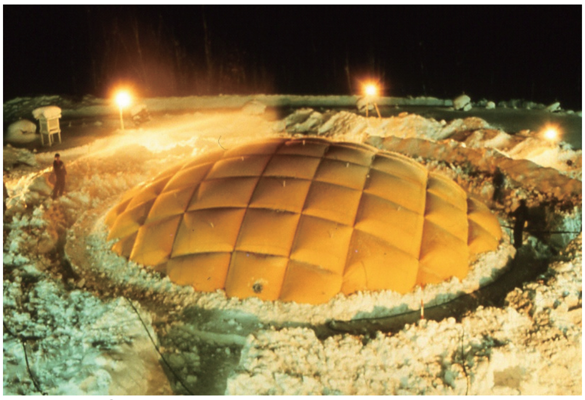
(b) Air inflated membrane

(c) Application of snow and water

(d) Removing membrane

Fig. 2: Construction sequences of 15m ice dome* constructed by students of Tokai University [6]

The air-inflated formwork consists of a 2 dimensional 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 circular membrane as shown in Fig.3 (a),(b),(c). A free shaped ice shell can be built using a non-circular membrane bag and a grid pattern of cover rope as shown in Fig.3 (d).



(a) Circular membrane bag (15m diameter)
+ Grid pattern[13]

(b) Circular membrane bag (20m diameter) +
Hexagonal and Pentagonal pattern from Geodesic[11]

(c) Circular membrane bag (30m diameter)
+ Triangular pattern from Geodesic division[12]

(d) Non-circular membrane bag
+ Grid pattern

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

The structural material of ice shell must be not snow but ice because ice is far better than snow in the mechanical property. The important objective of this construction work is to produce a high quality of artificial ice quickly on the formwork. Referring to Fig. 4, special attentions should be paid on the following points for this purpose [7];

(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^{o}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.

Workers can go up on the ice dome under construction 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 [8].

(e) The amount of the total 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).

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

Where T_a is outside air temperature in ^oC 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^{o}C, W_v becomes 38.8 *l*/min and W_v becomes 61.6 *l*/min for T_a=−20^{o}C.

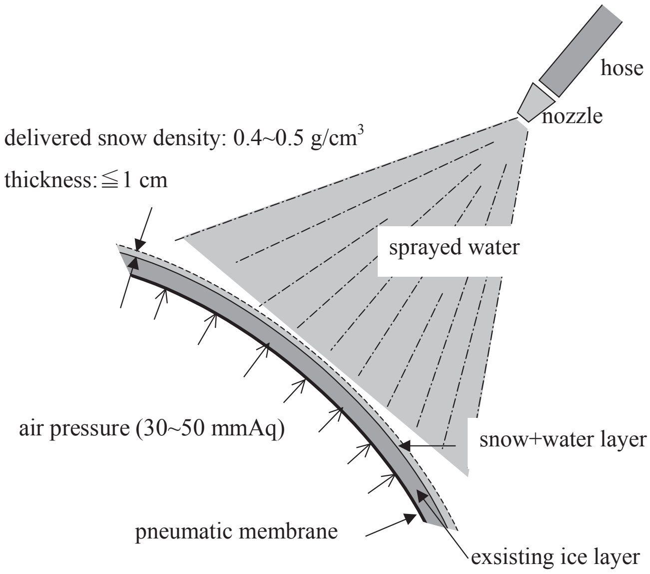


Fig. 4: Application of snow and water

2.3 Structural design

The ice temperature in ice shell is between 0 ^{o}C and –5 ^{o}C. The ice in this range creeps easily, and the deflection of the structure increases with time, even if there is no increase in the working stress. According to the results of the past field experiments of ice domes spanning 10 to 30 meters[2],[10],[11],[12],[13], the followings 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: stationary creep stage.
2. The deflection rate increases with time until collapse: tertiary creep stage.
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.

The visible deformation predicts the danger of collapse in advance. This is one of the most important reasons why the ice shell can be used as an architectural structure. In order to delay the speed of the deterioration caused by various weather conditions such as solar radiation, plus air temperature and rainfall during the period of the use, a low density of snow is blown onto the ice shell by a snow blower because the snow has a high performance in the thermal insulation. In order to recover the quality of the ice, spraying water onto the shell should be carried out a few times during the period. These devices for the maintenance make the life span of the ice shell longer,

Much has not yet been known about the creep phenomenon up to now and so following structural design guides are proposed in order to get sufficient structural safety against creep behavior of a large ice shell;

(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 should be less than 10 N/cm^2, which corresponds to about 1/40 to 1/50th of the uniaxial compressive strength of the ice.

3. Current Applications

Almost 30 years since 1980s, the shells have been 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

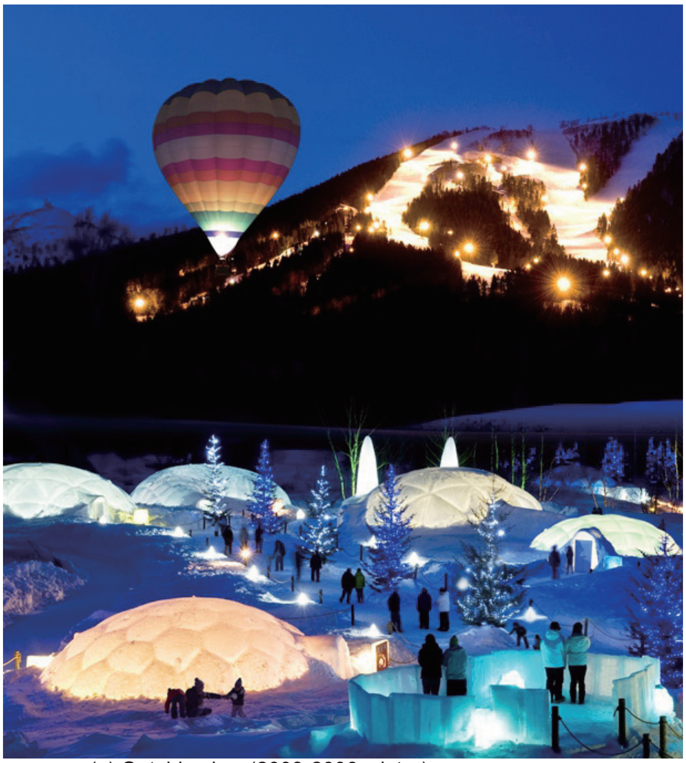
Table1: Meteorological Data (1981-2010)(http://www.jma.go.jp/jma/index.html) and Usage

Construction site	January~February		Usage (year)
	Average air temp.(C^o)	Precipitation(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~)**

making Japanese "sake", an indoor ice fishing on a frozen lake and event facilities for winter festival etc. [3]. As the typical examples of the applications, two examples, ‘Ice Village in Tomamu’ and ‘Ice Pantheon Project in Asahikawa’ are described here referring to Table 1.

3.1 Ice Village in Tomamu

Since 1997 in Tomamu, many ice shells, especially 10~15m ice domes* which use 10~15m diameter of circular membrane bag are being used each winter for about 75 days as leisure-recreational facilities in a ski resort.



(a) Outside view (2008-2009 winter)

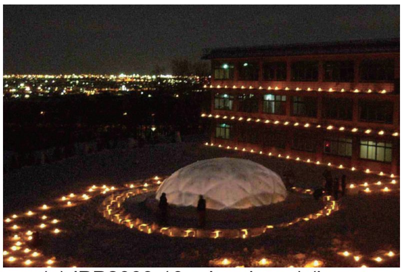
(b) Ice hotel

(c) Café bar

Fig. 5: Ice Village in Tomamu

3.2 Ice Pantheon Project in Asahikawa Campus of Tokai University

In addition to the numerical results of a theoretical analysis [9], the past construction experiences and the field experiments of 20~30m ice domes* [10], [11], [12] would support the realization of a huge ice dome spanning 40 meters never existed before, which has comparable 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. It can be said that ice is a convenient educational material for the students to study architecture and design.



(a) IPP2009 10m Ice dome* (base diameter=8.6m, height=3.0m)

(b) IPP2010 15m Ice dome* (base diameter=12.6m, height=5.0m)[6]

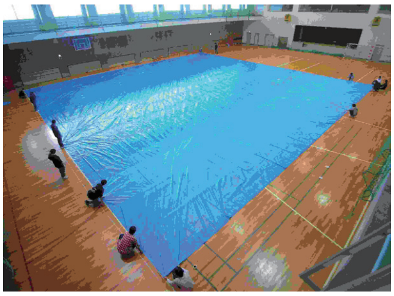
(c) IPP2011 20m Ice dome* (base diameter=16.0m, height=6.3m)

Fig. 6: Ice domes in IPP (Ice Pantheon Project) 2009-2011

Towards the realization of the ice dome spanning 40 meters, so called ‘Ice Pantheon’, the students started to go on an exciting, thrilling and wonderful voyage under the technical guidance by the authors of Tokai University. In winter of 2009, as the first step toward this end, a small size of 10m 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 winter of 2011, the students tried to construct a non-spherical 20m ice dome* which was not practically used before, although three 20m ice domes* were constructed for creep experiments in the past [10],[11]. Fig. 6 shows three ice domes constructed in IPP2009-2011.

And then, in this winter of 2012, a non-spherical 25m ice dome* was constructed successfully. Fig.7-12 shows the photos of the working sequences up to the completion.

Fig. 7 shows some scenes of the manufacturing processes for the pneumatic formwork consisting of a 2-D circular membrane bag and a cover rope. The membrane bag is fabricated by gluing along the periphery after wrapping in two pieces of plane sheets with 25 m in diameter. Although a P.V.C. membrane is normally used for ice shell construction, a polyethylene sheet is chosen in IPP2012 because of a financial reason. The specifications are as follows. Polyethylene blue sheet #3000, Weight: 152 g/m^2, Tensile strength: longitudinal 120 N/cm, traverse 110 N/cm. The geometry of the cover rope is determined by the geodesic Triacon division 6 frequencies of a non-spherical shape. Φ14 mm polypropylene rope is used for the manufacturing and the tensile strength of the rope is 30 KN.


(a) 25m square polyethylene blue sheet


(b) Gluing for 25m diameter 2-D circular membrane bag


(c) Manufacturing for polypropylene cover rope

Fig. 7: Preparation for pneumatic formwork (IPP2012)

Fig. 8 shows some scenes in the construction processes of the snow-ice foundation ring. 30 rope-anchors are equally located on a circle at the base. The size of the foundation ring has 21.2 m inner diameter, 1.2 m in height and 1.3 m in width. Therefore, much snow is needed for the construction and a heavy power shovel machine is used for carrying and putting snow. It takes almost one week in total for the completion from the site surveying.


(a) Site surveying

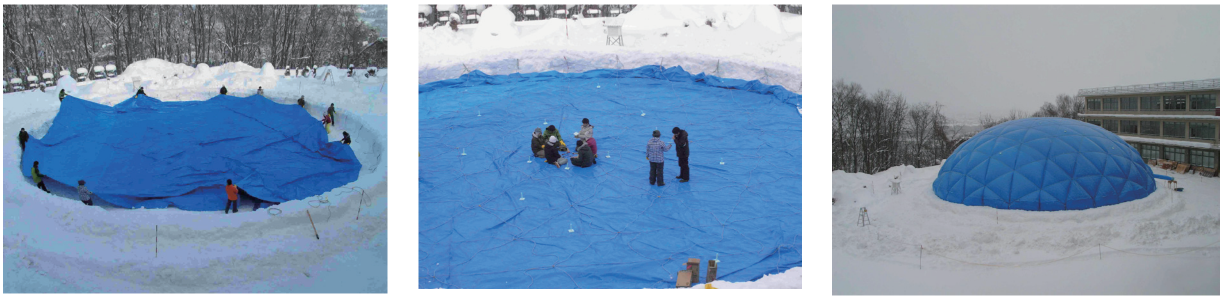

(b) Putting snow and pouring water


(c) Completion

Fig. 8: Construction of snow-ice foundation ring (IPP2012)

And then, as shown in Fig. 9, the inflation of the formwork is carried out after setting the 2-D membrane bag and covering the reticulated rope. A portable air blower, which has a capacity of 45 m^3/min maximum air flow and 500 Pa maximum air pressure, is used for the inflation, so the inflation time is very short, within one and half hour.

Application of snow and water is carried out under -10 C^o for producing a high quality of ice on the formwork, as shown in Fig. 10. The formwork has very large size which has 21.1 m base diameter and 8.0 m height, therefore the equipments for blowing snow and spraying water should be carefully chosen. The snow blower machine has capacity of more than 25 m in maximum snow throwing distance. A Φ 40mm hose with a high pressure pump engine is used for spraying water onto the milled snow. The total amount of spraying water is 130-230 litter/minute. The ice thickness of the completed dome is approximately 20 cm in average and the application time in total is almost 40 hours.

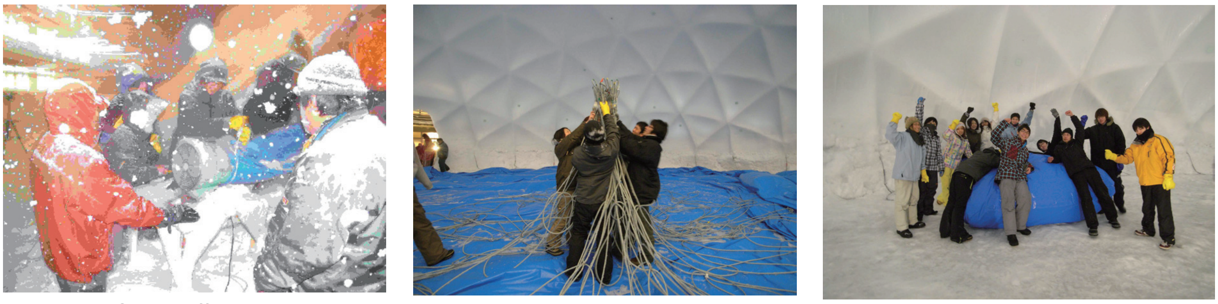


(a) 2-D membrane (b) Setting cover rope (c) 3-D air inflated formwork

Fig. 9: Setting pneumatic formwork (IPP2012)

(a) Blowing snow (b) Pump engine for high pressure (c) Spraying water

Fig. 10: Application of snow and water (IPP2012)



(a) Switch off air blower (b) Removing rope (c) Folded membrane

Fig. 11: Removing pneumatic formwork (IPP2012)

(a) Outside view (b) Jazz piano concert

Fig.12: 25m ice dome* (base diameter=21m, height=8.1m) used for event (IPP2012)

After the long application time of snow and water, the pneumatic formwork is deflated. The air blower machine is switched off at first. And then one of the authors enters into the inside periphery of the dome under deflation in order to confirm the structural safety. After a while, students come in and then remove the cover ropes and the membrane bag as shown in Fig.11. It takes a few hours in total for the deflation. The formwork can be understandably reused.

After the completion of 25m ice dome*, the dome was lighted up and then used for jazz piano concert as shown in Fig.12.

4. Ending Remarks

Water liquid changes into ice in solid under subfreezing temperature. Ice exists abundantly during winter season in severe cold regions. Ice has low mechanical properties compared to other construction materials such as steel, reinforced concrete and timber. However, if ice is used as structural material for shell structure, the ice structure is able to cover a wide area without supporting column and it can be used as a temporary building during winter in snowy and cold region.

It was 1980 when the development towards the realization of a large ice shell started. 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 construction rationality. The ice structure has also high structural efficiency as a shell. And then the shell creates a beautiful space in the environment from the translucent thin plate and the unique curved surface shape. Furthermore, the shell is environmentally compatible because it simply returns to the earth as water in spring.

Although there still remain to be studied in more detail about the construction technique, the structural design and the maintenance method of the ice shell as a special temporary structure, it has a possibility to become a useful structure common in not only inland Hokkaido but also severe cold regions all over the world.

Note

*. '*X*m ice dome' means the ice dome constructed by using *X*m diameter of circular membrane bag in the formwork before inflation.

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