FIELD STUDY OF A 30-M SPAN ICE DOME

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SUMMARY

A field study on both the construction and creep test of a 30-m span ice dome (25 m in base diameter, 9.2 m in height and 25 cm in average ice thickness) was carried out at Tomamu in Hokkaido during the winter of 2001. It took only six days for the completion of the big dome by the construction method of blowing snowand spraying water onto an air-inflated membrane as formwork. Following the construction, a creep test was executed under the winter natural environment in Tomamu and the structural behavior up until the collapse was examined. As a result, the central part of average displacement rate from February 17th to March 23rd, was about 6.5 mm/day, and it was shown that the dome had a good enough structural efficiency. Based on the result of this study, the future application of a 30-m span ice dome for an architectural facility could be basically possible.

Keywords: *30-m Span Ice Dome, Construction Test, Creep Test.*

1. INTRODUCTION

Snow and cold enable the application of an ice shell, which provides an efficient solution to certain problems in snowy and cold regions. The ice shell is thin, and its structural material is ice. It is a new type of ice structure based on modern structural engineering and it can cover a larger area compared to the classical snow-ice structures such as "Kamakura" or "Igloo". It had been suggested that the ice shell could be used for creating a rather unique built environment as a new idea of architectural technique in the snowy and cold regions during winter [1], because it has a special shape and a half-transparent texture of the ice.

An attempt never experienced before to construct ice shells for an architectural space, had been developed in Tomamu, Hokkaido since 1997 [2]. Many ice shells have been used as leisure space for visitors about 3 months in each winter and these have created a fantastic and beautiful space providing quite a unique built environment in winter. 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 study, a large ice shell with spans from 20 m to 30 m might be possible to use as an architectural structure. And then, 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 years 1999 and 2000. These test-domes had shown a high structural efficiency, and it concludes that a 20-m span ice dome is possible to use as an architectural structure [3].

Following the successful experiment of a 20-m span ice dome, a field study on both the construction and creep test of a 30-m span ice dome (25 m in base diameter, 9.2 m in height and 25 cm in average ice thickness) never existed before, was carried out at Tomamu in Hokkaido during the winter of 2001, searching the possibility of the realization from the aspect of architectural engineering. Based on the result of this study, it concludes the application of a 30-m span ice dome for an architectural facility could be basically possible.

2.CONSTRUCTION TEST

2.1.Outline of Constructional Sequence

1. Constructing snow-ice foundation with about a 25 m inner diameter.
2. Building up the 3-dimensional formwork by inflating a 2-dimensional membrane bag of 30 m

diameter, covered with ropes with a reticular pattern determined by the geodesic division anchored to the snow-ice foundation.

3. 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 in the vicinity of the top. Solidifying the thin layer snow-ice sherbet due to cooling by cold outside air.
4. Repeating the application of snow and water up to the 25 cm shell thickness. Then removing the bag and ropes for reuse.

2.2. Snow-ice Foundation Ring

The construction was done from February 4th to 6th in 2001. Following the measurement and readjustment of the site on February 4th, a heavy machine as shown in Figure 1 was used for the construction of the ring with about 25 m in inner diameter. 40 rope-anchors were located equally on the inner circle and at the base, preventing the rise in dome from excessive height caused by the 5 % elongation of the P.P. rope.

Fig. 1. Construction of snow-ice foundation ring

2.3. Air-Inflated Formwork

The formwork consists of membrane bag and covering rope.

1. The membrane bag is fabricated by welding along the periphery after wrapping in two pieces of plane sheets with 30 m in diameter. The specifications of the membrane are as follows.

   P.V.C., T-SF 100%, weight: 530~570 g/m^2, Tensile strength: longitudinal 150±20 kg/3cm, Transverse 110±20 kg/3cm, Color: dark-green.

2. As shown in Figure 2, the geometry of the net was determined by the geodesic Triacon division 8 frequencies. The net was made of ϕ 14 mm polypropylene rope and its length shown in Figure 3 between points was calculated by Spherical trigonometry, supposing the design section shown in Figure 4. Supposing maximum water head of a portable blower as 46 mm aq., the tension force become about 1 ton on computation, so the 14 mm P.P. rope is strong enough against 3 tones of its breaking force.

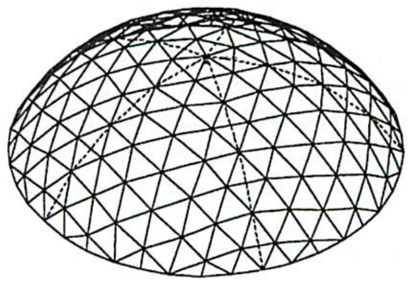

Fig. 2. Reticular pattern

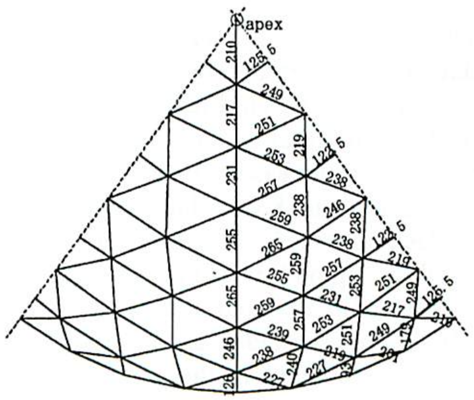

Fig. 3. Rope length (cm)

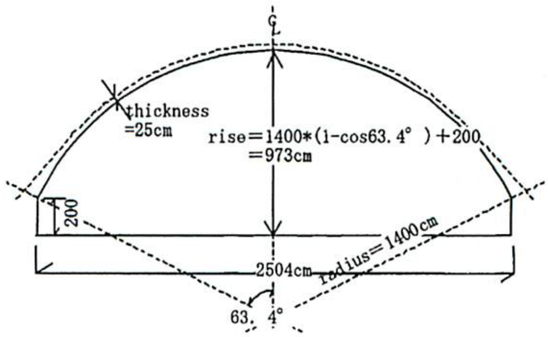

Fig. 4. Design section

2.4. Inflation

The first inflation test was carried out on February 7th. A portable blower, which has a capacity air-flow of 44 m^3/min., was used for the inflation, so the inflation time should be within about 1 hour on the computation. However, because of some troubles such as an adjustment between the membrane and ropes, it took several hours for the inflation beyond the theory. Figure 5 shows the air-inflated formwork after the inflation. On February 12th, just before the application of snow and water, about 40 pieces of Styrofoam sticks for checking the shell thickness under the construction were prepared on the membrane. However, as the adhesive agent was not effective because of a very low air temperature of −13 °C below at that moment, almost all of them were not attached on the membrane. So, the rational method of attachment should be devised in future construction.

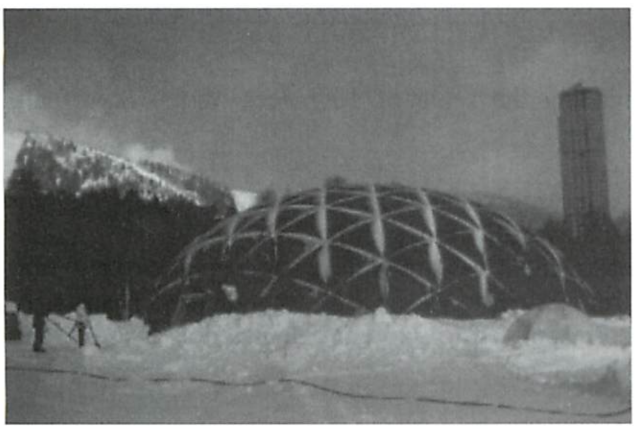

Fig. 5. Air-inflated membrane as formwork

2.5. Application of Snow and Water

Application of snow and water was carried out from February 12th evening to 16th early morning. As shown in Figure 6, it was very nice weather to construct ice shells at that period. Figure 7 shows the situation under construction. A ϕ 40 hose and six ϕ 20 hoses were used for spraying water onto the milled snow. Total amount of spraying water was 240 –290 litter/min.. It is assumed that the ϕ 40 hose normally supplied 150-200 litter/min. ϕ 20 hoses were continuously operated on five high stages, and ϕ 40 hose was intermittently used moving around the dome according the situation. On the other hand, blowing the milled snow onto the membrane was carefully done by two snowplows so as to keep the snow thickness less

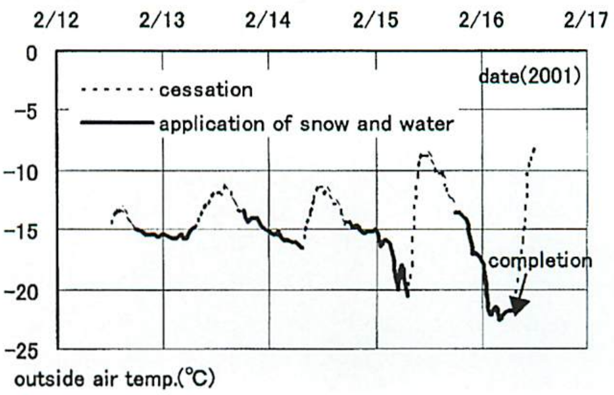

Fig. 6. Outside air temperature under construction

Fig. 7. Application of snow and water

than 1 cm during one operation. The one with the capacity of 22 m maximum throwing distances was used for blowing the snow except the vicinity of the apex. The other with 30 m throwing distances was applied in case of the central parts of the dome. It is assumed that the thickness of the completed dome was approximately 25 cm in average. It took 2 hours to get 1 cm ice thickness in this experiment because it needed 56 hours in total time for the application of snow and water.

2.6. Deflation

The air membrane bag began to deflate at 8 a.m. on February 16th. Figure 8 shows an inside view under deflation. It took about 5 hours to remove the air out of the bag, and then the membrane was folded and pulled out the dome. Figure 9 shows the exterior view of the completed 30 m span gigantic ice dome as never seen before.

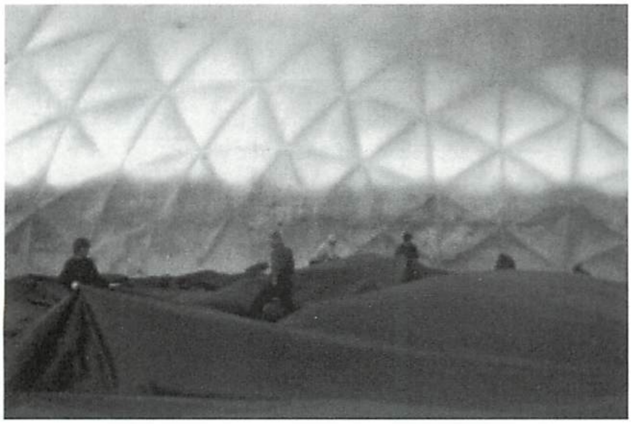

Fig. 8. Deflation

Fig. 9. Completed ice dome

3. CREEP TEST

In order to prove the actual possibility of application to an architectural structure in case of such a huge ice dome, the structural property of the completed ice dome was examined up to the collapse which occurred on April 10th. After the automatically measurement, the structural behavior was observed by eye up to the collapse. The results of this test were made in comparison with the structural behaviors of the 20m span ice dome in 2000 [3].

3.1. Ice thickness and Geometry

At the beginning of the deflation, the preparation of the point for measuring displacement and the measurement of ice thickness, as shown in Figure 10, were done at the same time. As a result, the thickness at the upper part of the dome was 22 cm to 26 cm. The thickness at the middle and lower parts of the dome were measured by carefully

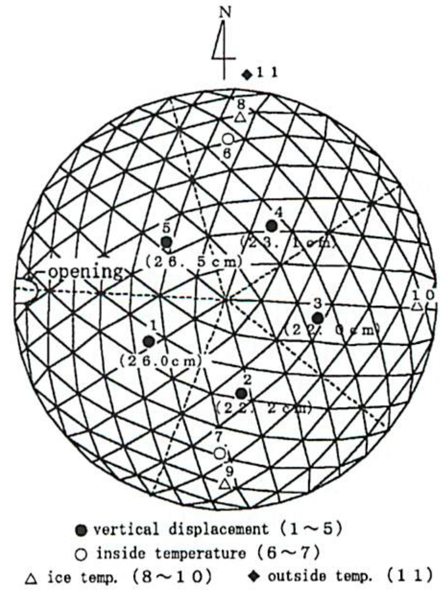

Fig. 10. Ice thickness and measuring points for vertical displacements & temperatures

reading the scale of 10 pieces of the Styrofoam sticks.

As a result, the thickness at the west side (windward side) was distributed from 25 cm to 30 cm, and the east side (leeward side) was comparatively thin from 22 cm to 27 cm. The top height 921 cm fairly corresponded to 926 cm calculated as 5 % of rope elongation.

3.2. Displacement and Temperature

Displacements and temperatures were automatically measured from February 17th to March 23rd. 5 points for measuring vertical displacements and 6 points for measuring temperatures (One point of outside, two inside, and three ice temperatures) are shown in Figure 10. Figure 11 shows the method of measuring a vertical displacement. A programmable data logger recorded these displacements automatically at 3-hour intervals. A self-recorded thermometer measured the temperatures at 1-hour intervals. Figure 12 shows temperature-time curves during the whole period [However, the outside air temperatures (Tout) from March 4th to March 13th were not shown here, because it was noticed later that the outside thermometer was embedded in the snow]. Table 1 shows average temperature at every point. It recognizes that Tout, the inside air temperatures (Tin) and the ice temperatures (Tice) were

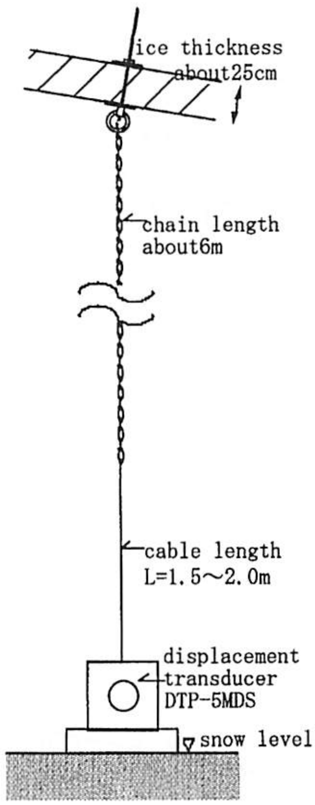

Fig. 11. Measuring method

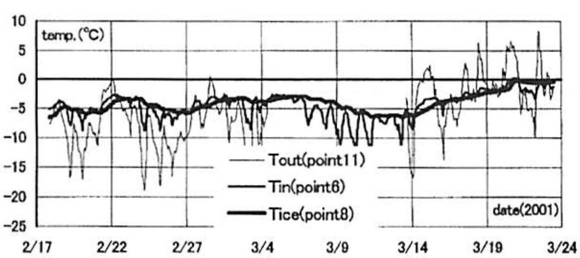

Fig. 12. Temperature-time curves

Table 1. Average temperature (°C) (2/17~3/23)

Tout	Tin		Tice		
(point11)	North (6)	South (7)	North (8)	South (9)	East (10)
−4.9	−4.5	−4.5	−3.9	−3.2	−3.9

low in order. Tin was low in average and its change was very large, because the cold outside air entered easily into the inside from the opening installed the windward side. Figure 13 shows 5 points of displacements-time curves during the same period. The behaviors of these points were almost same quantitatively and qualitatively. As shown in some examples, about 150 mm downwards displacement from March 20th to 21st, about 190 mm upwards from March 21st to 22nd, unbelievable large change of displacement occurred all over the record and it seemed that Figure 13 did not show true displacement behavior. And then, in order to seek the reason, various aspects such as the thermal expansion of ice or chain, the movement of snow level by freezing and the influence of the crack near the opening were checked both quantitatively and qualitatively. However, as the result, these factors did not seem to give rational reason for the phenomenon. At last, the influence of the temperature on the displacement transducer was investigated experimentally. Figure 14 shows the displacement, temperature – time curve under the condition that the transducer was installed between two fixed points. As a result, as seen in the example that 45 mm changed against 13 deg. in temperature change, the temperature change clearly had a big influence on the displacement transducer. Furthermore, in the same figure, the displacement curve was approximately fitted to the straight line by the method of least square mean and the slope of the line became 0 which means no movement between

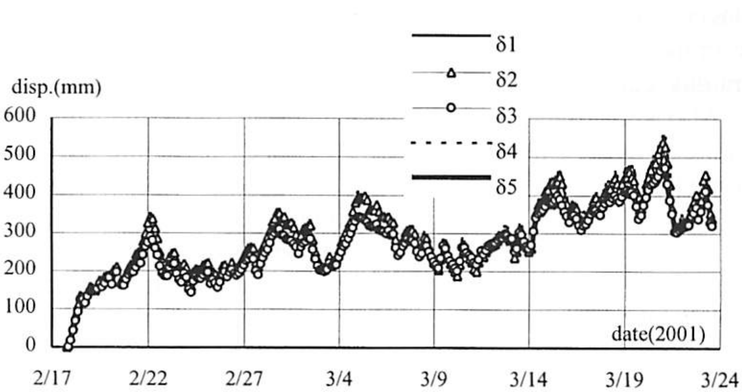

Fig. 13. Vertical displacement-time curves

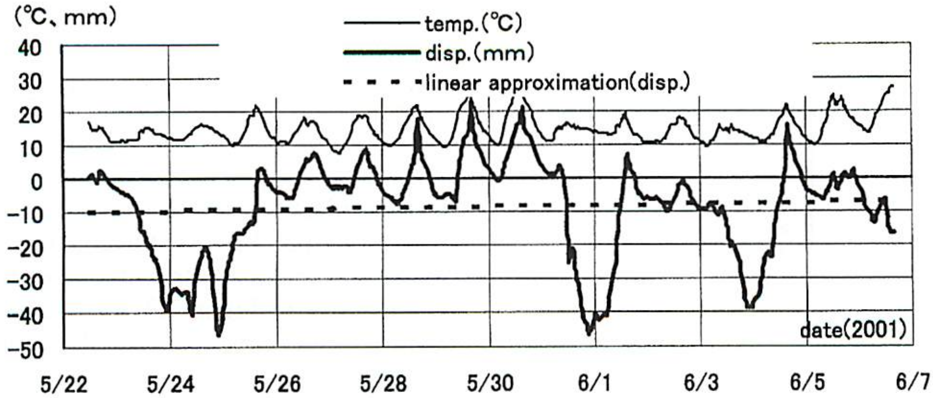

Fig. 14. Check of displacement transducer

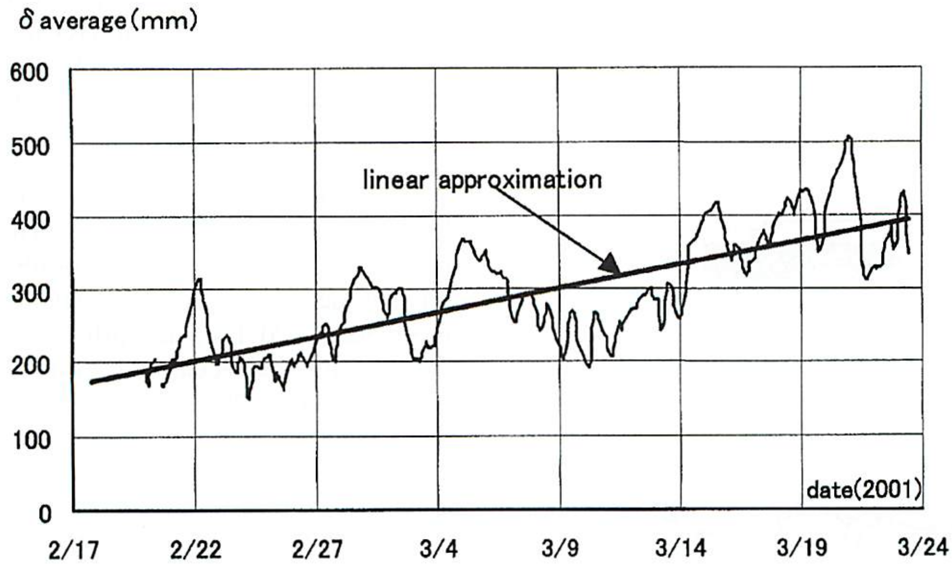

Fig. 15. Linear approximation of displacement curve

two fixed points. Based upon the consideration, as shown in Figure 15, the method was applied to the average displacement of 5 curves shown in Figure 13 and its average displacement was computed as 6.5 mm/day. This value coincides very well with the value 5.4 to 7.2 mm/day calculated from the membrane shell theory, Maxwell' linear viscose material and the 3 to 4 mm/day in the experimental study of 20 m span ice dome [3].

3.3. Behavior of Collapse

After removing the displacement transducers on March 23rd, the structural behavior was observed by eye up until the collapse, which occurred at about 1 p.m. on April 10th. In this case, the behavior was "brittle" never seen at the previous experiment, as a large deformation was not observed before the collapse. It indicates that the collapse does occur abruptly, and the prediction of the collapse is difficult by eye observation. Therefore, brittle collapse is not suitable for the architectural structure which needs enough time to predict the danger of the collapse. Future experiments of a 30-m span ice dome should be confirmed whether such a large shell brings the brittle behavior of collapse or not. The broken pieces of ice plates at the south side were very poor due to the damage by solar radiation. It is suggested to spray water and blow snow onto the dome several times during its application, as the easy method for keeping the quality of ice which means improvement of the structural safety of the ice dome. Figure 16 shows the temperatures during until the collapse. After

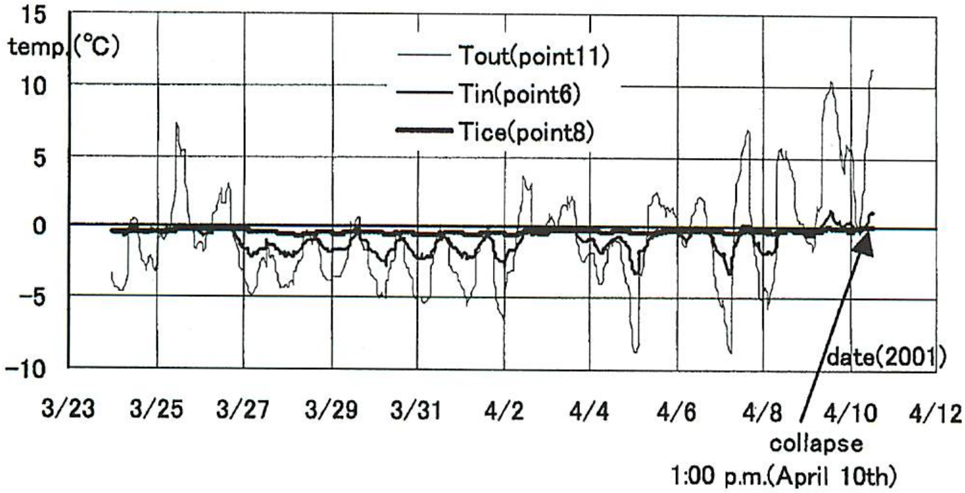

Fig. 16. Temperature-time curve before collapse

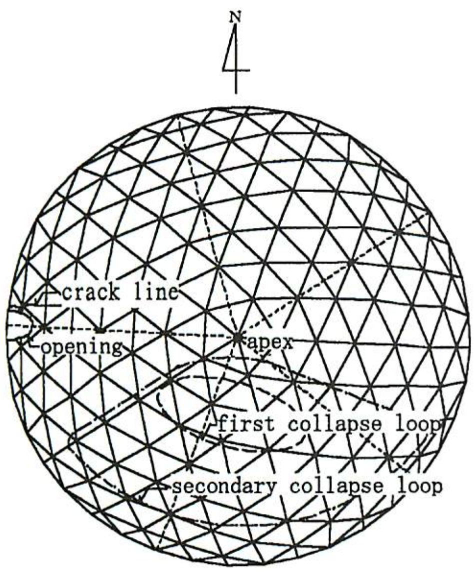

Fig. 17. Behavior of collapse

Fig. 18. Exterior view just after collapse

April 2nd, the outside air temperature often exceeded 0°C and the sunshine became strong. According to an on-site observer, the weather condition promoted rapidly, the melting ice of the dome and the sound of the melting echoed inside. Figure 17 shows the sequential order of the collapse. The first collapse occurred at the middle of the south side where the sunshine was the strongest over the dome. Furthermore, the crack besides the opening was not so spread and did not affect the structural behavior. Figure 18 shows the exterior view after the second collapse.

4. CONCLUSION

According to the membrane shell theory, the compression stress at the apex of this dome covered uniformly with 50 cm snow depth (corresponding to 100 kg/m^2 vertical load) is computed as about 1 kg/cm^2 which is about 1/40th of the uniaxial compressive strength of an ice. This is the simple reason why the 30-m span ice dome has enough strength to exist structurally. Therefore, an actual proof test of 30-m span ice dome concerning to the construction technique and the structural safety was challenged at Tomamu, Hokkaido in winter of 2001.

As a result, it is concluded that the application of a 30-m span ice dome for an architectural facility could be basically possible. This construction method of blowing snow and spraying water onto an air-inflated membrane as formwork, is very rational for a large ice shell because it needed only six days for the completion of the 30-m span ice dome. And then, it is confirmed the completed dome had a high structural efficiency, because its average displacement rate at the central part of the dome was estimated 6.5 mm/day during the winter period and the collapse occurred on April 10th after the outside air temperature often exceeded 0°C and three days over 0°C in average air temperature lasted.

Taking the actual construction equipments such as the snowplow for blowing snow and the adjustable nozzle for spraying water into consideration, the size of the ice dome may be limited up to 30-m span so far. However, it would be possible to construct a 40-m span ice dome if the equipments were prepared. Pantheon in Rome constructed in about 120 A.C. is well known as one of the biggest classical stone dome and its size has about 40 m in base diameter. The ice material is easier to manufacture than stone and its strength/density is better than stone in short term loading, so it could be possible to realize structurally such a size of ice dome instead of a stone dome. On the other hand, the ice is a half-translucent material, so the ice shell creates a fantastic, beautiful space providing quite a unique built environment in winter. Particularly, in case of a large span, it will be more exciting artistically and getting more useful to apply to various kinds of architectural facilities for winter events.

A 30-m span ice dome is quite a huge ice shell never experienced before, so its structural behaviors are not known as well. Therefore, the confidence of its structural reliability is not enough at all, even though this first experiment was successful. Toward the realization of the 30-m span ice dome for architectural structure, the untiring field studies concerning to the reliability of its structural safety and the improvement of the construction technique will be needed much more in the future.

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