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Field Experiment of Ice Dome Spanning 20~30 Meters

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ABSTRACT

Aiming at the realization of a large ice shell to be used for a variety of architectural facilities in winter, experimental studies of ice domes spanning 20~30 m have been carried out at Tomamu since 1999. Two field studies of a 20-m-span ice dome (17-m base diameter and 6.5-m height) were developed in 1999–00. These test domes showed a high structural efficiency, so in the winter of 2001 the experimentation was taken a step further by carrying out a field study focusing on both the construction and creep test of a 30-m-span ice dome (25-m base diameter and 9.2-m height). Based on the findings from these studies, it can be concluded that the application of an ice dome spanning 20~30 m should be feasible.

INTRODUCTION

Snow and frigid conditions enable the application of an ice shell, which would provide an efficient solution to certain problems common in cold and snowy regions. The shell is thin, and its structural material is ice. A new type of ice structure based on modern structural engineering, it can cover an area larger than the classic snow-ice structures such as the Japanese *kamakura* or the igloo. It was suggested that the ice shell, as a concept in architectural technique in cold and snowy regions during winter, could be used to create a unique built environment (Kokawa, 1985). Since experimentation in the construction of ice shells for architectural space began in Tomamu, Hokkaido in 1997 (Kokawa et al., 2000), many ice shells have been made for actual use, providing a unique built environment for visitors for about 3 months each winter. Taking architectural safety into consideration, the size of these shells had been limited to no more than a 15-m span. However, extensively interpreting the results of the past studies, a large ice shell with a span between 20 m and 30 m would also be possible to use as an architectural structure. And then, two field studies on a 20-m-span ice dome (17-m base diameter and 6.5-m height) were carried out at the same site in Tomamu in 1999–00. These test domes showed a high structural efficiency. Following the experiments with 20-m-span ice domes, a field study on both the construction and creep test of a 30-m-span ice dome (25-m base diameter and 9.2-m height) was carried out at the same place during the winter of 2001, 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-span ice dome for an architectural facility would be practicable.

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KEY WORDS: 20~30-m-span ice dome, field experiment, construction test, creep test, winter architecture.
N.B.: "30-m span" refers to the diameter of the membrane bag used in the formwork before inflation.

SIMPLE CONSIDERATION

According to the membrane shell theory, the compression stress at the apex of a spherical shell (with a 30-m base diameter and 130° open angle) under the dead type of loading (ice density 0.85 g/cm^3) is computed as 7.0 N/cm^2, which corresponds to about 1/60th of the uniaxial compressive strength of ice. Thus, the 30-m-span ice dome has enough strength to stand, theoretically. This is the reasoning behind the field experiment of the 20~30-m-span ice dome concerning the construction technique—and the structural safety, which was subsequently conducted.

OUTLINE OF CONSTRUCTION METHOD

The *kamakura* and igloo are classic snow-ice structures, but it seems that these structure have neither construction rationality nor structural efficiency in the case of a large span. A *kamakura* is a traditional Japanese snow hut where children play house during the New Year holidays; it is formed by scooping out snow from a small mound of snow. An igloo is a snow hut built by arranging snow blocks hemispherically. In contrast, the ice shell is constructed by following a simple, quick and economical method:

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 a thin snow-ice sherbet layer (1 cm) by blowing the milled snow with a rotary snowblower, spraying water with a high-pressure adjustable nozzle, then letting it freeze naturally where temperatures remain at −10°C.
3. repeating the application of snow and water until the desired shell thickness (1/100th of the span) is reached, then removing the bag and ropes for reuse.

The ice quality of the completed dome can be judged satisfactory if there is sufficient outward transmission of light from the lighted interior.

FIELD TEST OF 20-M-SPAN ICE DOME

Theoretically, the use of an ice dome with a span between 20 and 30 m is feasible. However, the actual proof test of an ice dome this large had not been done before, except for the field experiment of a 20-m-span ice dome in 1985 (Kokawa and Murakami, 1986); more work was necessary to demonstrate its structural reliability for use as an architectural structure. Thus, with an eye

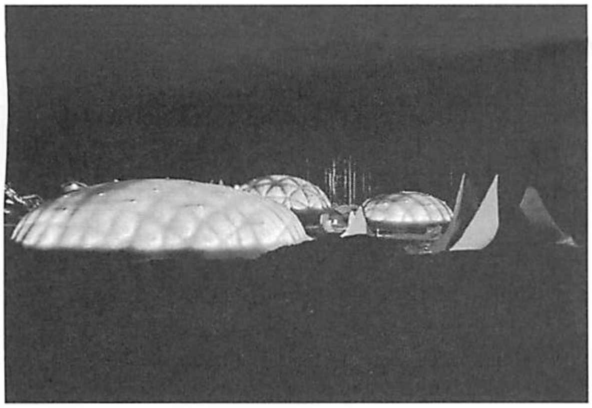

Fig. 1 Ice shells in Tomamu (1999–00)

toward the reliability of its structural safety and improvement of the construction technique, two field studies on a 20-m-span ice dome 6.5 m high were carried out at the same site in Tomamu in 1999 and 2000. These test domes showed a high structural efficiency compared with the first test dome constructed in 1985, which had geometrical and material imperfections because of inexperience in snow-blowing operations. The following describes the construction and creep test of the year 2000's test-dome, and concludes that a 20-m-span ice dome, as an architectural structure during winter in Hokkaido, is feasible.

The construction process is briefly described as follows. After the completion of the snow-ice foundation ring, with an inner diameter of about 17 m, 90 cm depth and 1 m width, a PVC membrane bag covered with a net was inflated as shown in Fig. 2. Fig. 3 shows the reticular pattern of the covered ropes based on a geodesic division. The polypropylene rope was 14 mm in diameter, with an equal length of 1.5 m between nodes. The central height of the inflated formwork was about 6.5 m. Milled snow was carefully blown onto the membrane by a rotary snow-blower with a maximum blowing distance of 22 m, and water was continuously sprayed onto the snow using 6 adjustable nozzles with a maximum spraying distance of 15 m and a total spraying amount of 60 liters/min. Fig. 4 shows the outside air temperature during the application of snow and water. The completed dome was assumed to have a 1040-cm radius of curvature and a 1720-cm base diameter, based upon the measurement of the central height and the inner diameter at the base. Fig. 5 shows the shell thickness at the locations. The ice thickness reading was unavailable for the part of the shell where the Styrofoam measuring sticks were coated with snow and water spray during construction. The intended shell thickness was 15 cm at the top, 17.5 cm at the

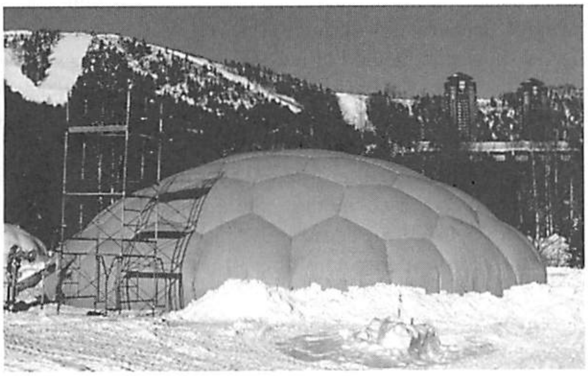

Fig. 2 Air-inflated membrane as formwork

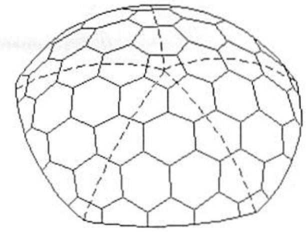

Fig. 3 Reticular pattern

middle part and 20 cm at the bottom, but the actual thickness was found to be 12.5 cm, 17.9 cm and 18.4 cm on average, respectively. The ice was comparatively thin at the bottom because of the steep slope. It took 2 h to reach a thickness of 1 cm in this construction, taking a total of 36 h to attain the average thickness of 17.9 cm. Displacements and temperatures were measured automatically between February 12 and March 27. Fig. 6 shows from which points these measurements were taken. The hanging method (Kokawa, 1985) was employed in measuring the displacement at 21 locations on the inside surface of the dome. A programmable data logger recorded the changes automatically at 3-h intervals. Temperature readings were taken at 1-h intervals, using a self-recording thermometer in 5 locations: 1 for exterior air temperature, 2 for interior air temperature, and 2 for ice temperature.

Fig. 7 shows temperature-time curves for the entire period. Figs. 8 and 9 show the displacement-time curves. Most noteworthy in these figures is the dramatic increase in deformation from March 4 to 6, when ice temperatures stayed close to 0°C during a period of warmer weather and stronger sunlight at the beginning of spring. During the other periods, the structural behavior was stationary, and the average creep displacement of $\delta_{0\ 5}$ was 2.5~3.0 mm/day, as shown in Fig. 8.

The third column of Table 1a and b qualitatively shows the temperatures and displacements during this period (3/4~3/7), and it can be seen that the nearly 0°C ice temperature causes the increase of deformation. Except for this period, as shown in Table 1b or Fig. 9, the structural behavior of the dome is stable, although δ_8 and δ_{13} at the south side are larger than the other δ. Concerning the results of the periods before and after 3/4–3/7, as presented in Table 1b, displacements during the earlier period, 2/14~2/29, in spite of its colder temperatures as shown in Table 1a, were larger than during the later period, 3/11~3/26, except for δ_8. Fig. 10 shows the 2000 dome's high structural efficiency compared to that of the '85 dome, which had geometrical and material imperfections (Kokawa et al., 1986). After the automatic measurements ended, the structural behavior was visually observed until the collapse, which occurred on April 4 following the appearance of a large deformation (Fig. 11).

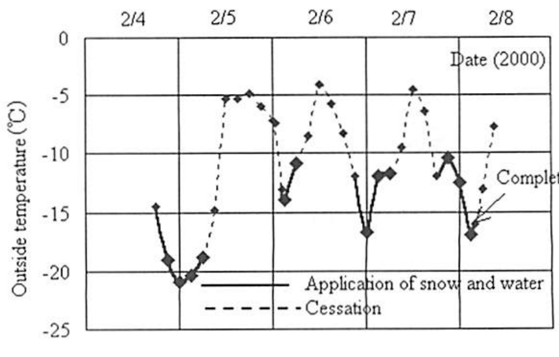

Fig. 4 Outside air-temperature during construction

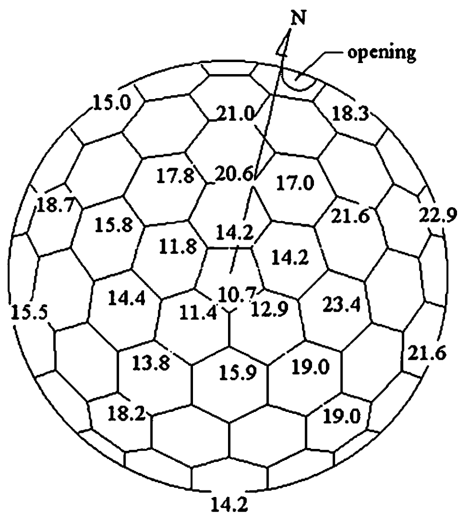

Fig. 5 Ice thickness (cm)

FIELD EXPERIMENT OF 30-M-SPAN ICE DOME

A field study involving the construction and creep test of a 30-m-span ice dome (25-m base diameter, 9.2-m height and 25-cm average ice thickness) was carried out at the same site during the winter of 2001. It took 6 days to complete the construction. Following the construction, a creep test was performed and the structural behavior examined. It was found that the average displacement rate in the central parts of the dome from February 17 to March 23 was about 6.5 mm/day, and it was shown that the dome had a sufficient structural efficiency.

The construction process is briefly described as follows. After the completion of the snow-ice foundation that had about a 25-m inner diameter and 180-cm depth, the 2-D PVC membrane bag, 30 m in diameter and covered with ropes with a reticular pattern, was inflated. Fig. 12 shows the reticular pattern of the covering ropes based on a geodesic Triacon division 8 frequencies. The

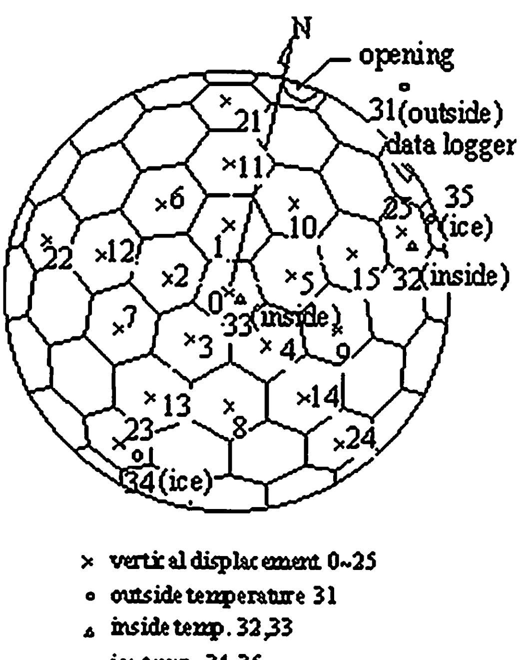

Fig. 6 Displacement and temperature measurement locations

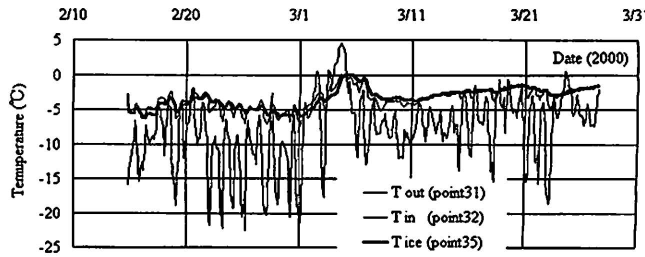

Fig. 7 Temperature-time curves

polypropylene ropes were 14 mm in diameter, and their lengths were determined by spherical trigonometry. Fig. 13 shows the inflated formwork with a central height of about 9.2 m. Snow and water were applied from the evening of February 12 to the morning of February 16th (Fig.14). Using 2 snow-blowers, each application was kept within a thickness of 1 cm. Fig. 15 shows the application of snow and water. One Φ40 hose and 6 Φ20 hoses were used for spraying water onto the milled snow. The total amount of water sprayed was 240–290 liters/min. Using the smaller hoses, water was sprayed continuously from 5 scaffolds placed around the dome. Additional water was sprayed in various places as needed, using the larger hose.

The deflation of the membrane bag was begun at 8 a.m. on February 16. Fig. 16 shows an inside view during the deflation. It took about 5 h, after which the membrane was folded and removed from the dome. Fig. 17 shows the exterior view of the completed ice dome.

In order to prove the actual possibility of application to an architectural structure in the case of such a large ice dome, the structural property of the completed ice dome was examined until its collapse, which occurred on April 10. After the automatic measurements were finished, the structural behavior was visually observed until the collapse. Then the results of this test and the 20-m-span ice dome in 2000 were compared.

At the beginning of the deflation, the measurement of ice thickness was taken at the 5 locations in the upper part of the dome. As a result, the range was from 22 cm to 26 cm. Readings were taken from 10 Styrofoam ice-thickness indicators in the middle and lower parts of the dome. It was found that the thickness on the windward side was from 25 to 30 cm, while the leeward side was comparatively thin, ranging from 22 to 27 cm. The average thickness of the completed dome was then inferred to be approximately 25 cm. It took 2 h to achieve 1-cm ice thickness in this experiment, taking a total of 56 h to complete.

Displacements and temperatures were automatically measured from February 17 to March 23. Fig. 18 shows 5 points for measuring vertical displacements and 6 points for measuring temperatures (1 outside, 2 inside, and 3 ice temperatures). Table 2 shows the average temperatures during the period.

Fig. 19 shows the method of measuring a vertical displacement. Although this method is basically the same as that of earlier experiments (Kokawa, 1985: Kokawa et al., 1986), the displacement transducers, DTP-5MDS (built-in reel type, measurable range up to 5 m) in this figure, are a different type from the strain-gauge type of transducers used in the experiments on smaller domes ranging from 5 to 20 m, because a larger deformation was predicted in the creep experiment of this 30-m-span ice dome. Fig. 20 shows the average displacement-time curve of the 5 points, whose displacements were very similar during the recording period. According to this curve, a roughly 150-mm downward displacement from March 20 to 21, a roughly 190-mm upward displacement from March 21 to 22, and other unexpectedly large changes

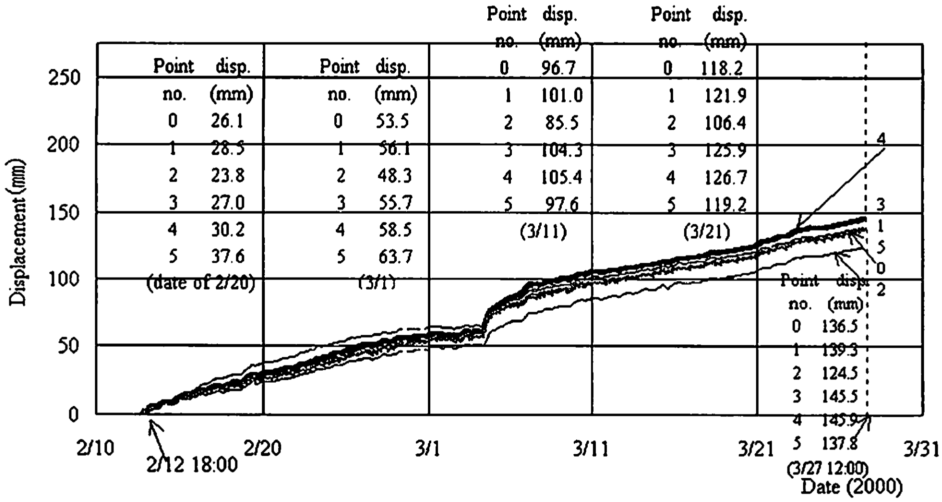

Fig. 8 $\delta_{0\ 5}$-time curves

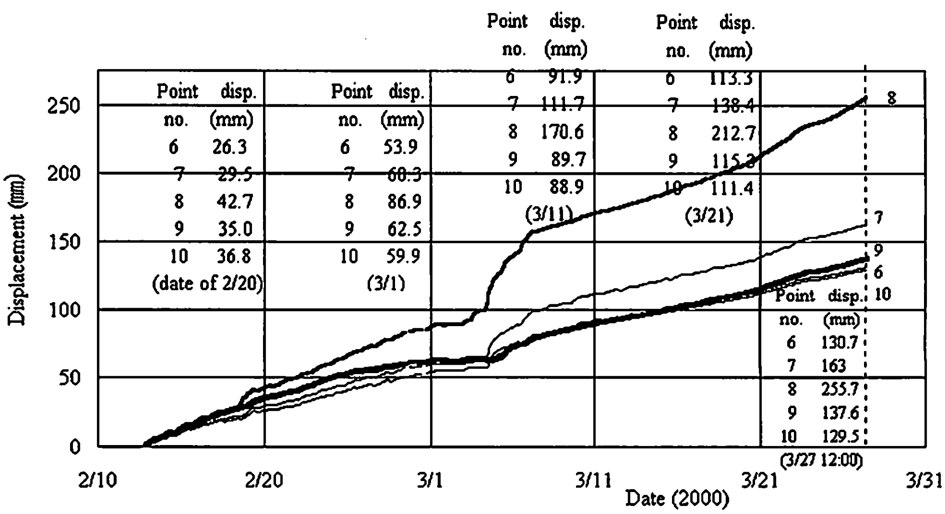

Fig. 9 $\delta_{6\ 10}$-time curves

Period Point no.	2/14~2/29	3/11~3/26	3/4~3/7	(2/14~3/26)
Outside (31)	−10.9	−6.5	−2.6	−8.0
Inside (32, 33)	−4.7	−2.5	−1.0	−3.4
Ice (34)	−4.5	−1.6	−0.3	−3.0
Ice (35)	−4.7	−2.4	−0.9	−3.4

Table 1a Average temperature (°C)

Period Points no.	2/14~2/29	3/11~3/26	3/4~3/7	(2/14~3/26)
0	2.8	2.5	9.3	3.0
(1,2,3,4,5)	3.0	2.5	9.3	3.0
(6,7,9,10)	3.2	2.8	6.7	3.1
8	4.8	5.2	18.6	5.7
(11,12,14,15)	3.5	2.7	8.3	3.3
13	4.7	3.1	15.4	4.5
(21,22,23,24,25)	3.7	2.7	8.7	3.5

Table 1b Average creep displacement (mm/day)

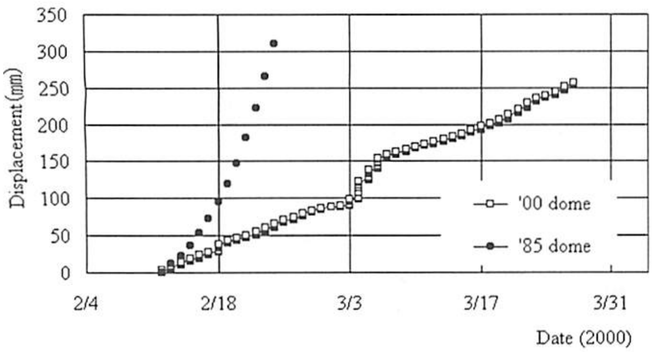

Fig. 10 Comparison between '00 and '85 dome

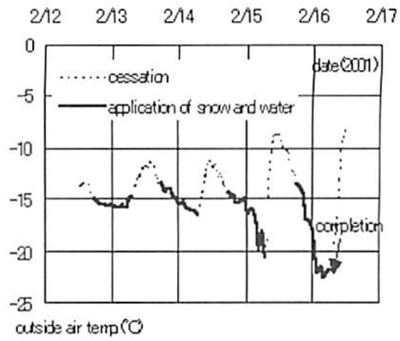

Fig. 14 Outside air temperature during construction

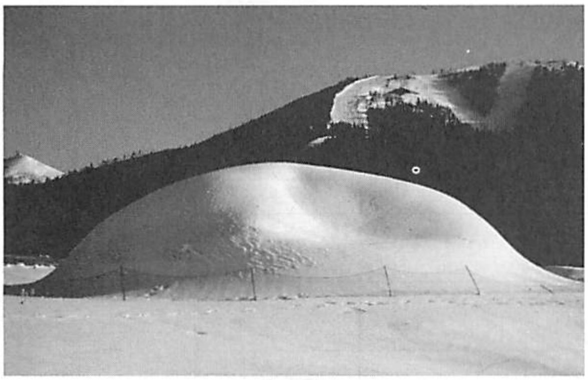

Fig. 11 Large deformation right before collapse

Fig. 15 Application of snow and water

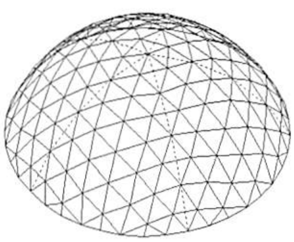

Fig. 12 Reticular pattern

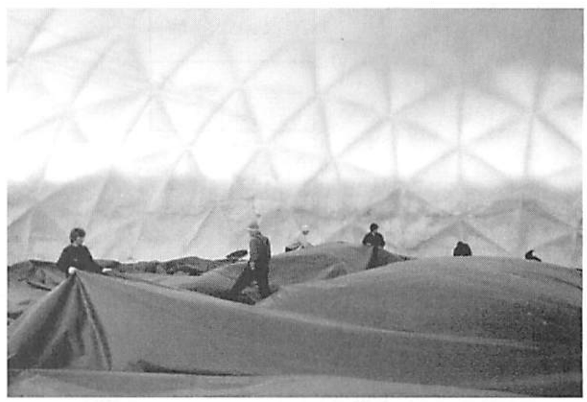

Fig. 16 Removing membrane

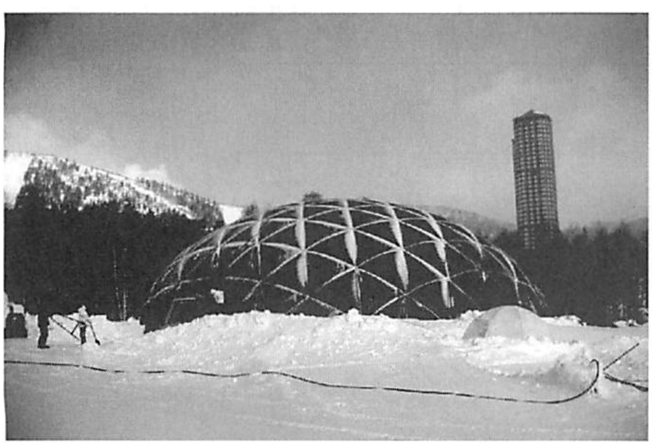

Fig. 13 Inflated membrane

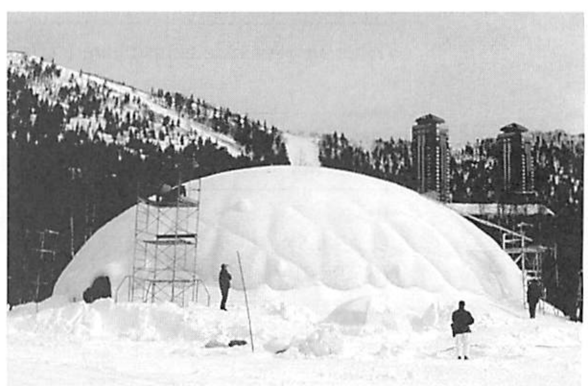

Fig. 17 Completion

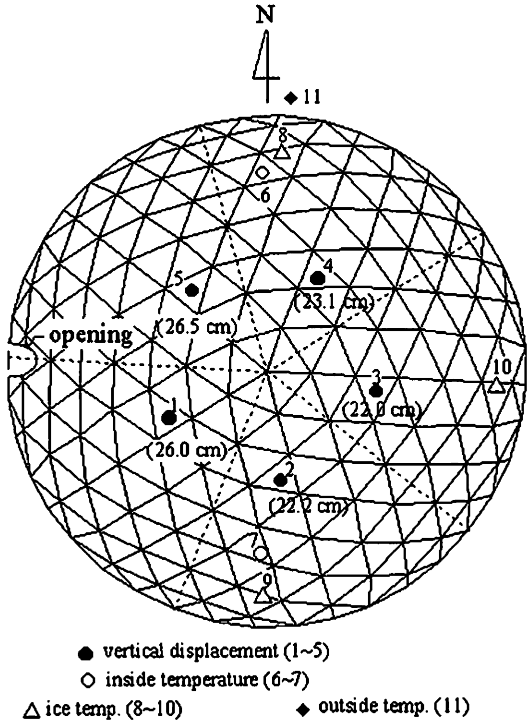

Fig. 18 Ice thickness and measurement locations for vertical displacement and temperature

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

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

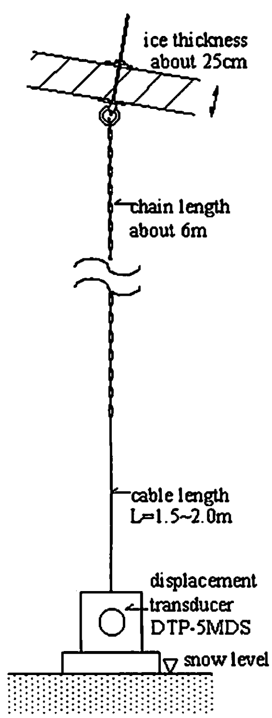

Fig. 19 Measuring method

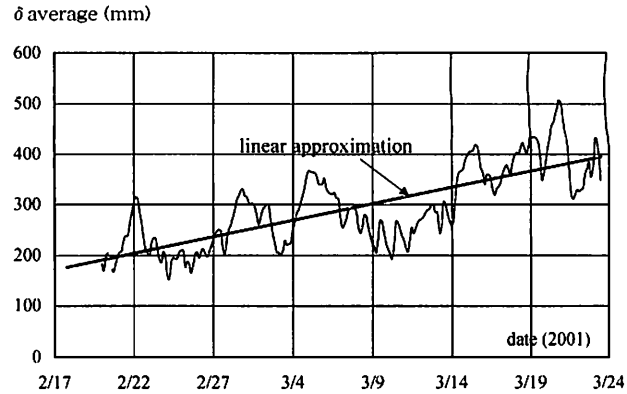

Fig. 20 Linear approximation of displacement curve

of displacement occurred throughout the recording period. However, it is doubtful that these readings reflect the true displacement behavior. Possible factors of influence were investigated, such as the thermal expansion of ice or the chain, temperature-induced height fluctuations in the snow floor and the crack near the opening of the dome, but these factors did not seem to give any rational reason for the phenomenon. In addition, the displacement transducers were tested for temperature influence. It was still not clear why the changes were so large. Fig. 20 shows the average daily creep displacement derived from the actual data using the least square method to fit the displacement curve to a straight line. The slope of the straight line representing the average creep 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 in connection with Maxwell's linear viscose material, and the 3 to 4 mm/day in the experimental study of the 20-m-span ice dome described above.

After removing the displacement transducers on March 23, the structural behavior was visually observed until the dome's collapse. Fig. 21 shows the temperature-time curves during the period. As seen in this figure, the outside air temperature often exceeded 0°C after April 2. According to an on-site observer, the weather conditions promoted the rapid melting of the ice, and the rushing sound echoed inside the dome. Then, following 3 consecutive days with an average air temperature of over 0°C, the collapse occurred on April 10, at about 1 p.m. The ice quality of the broken plates on the south side was very poor due to solar damage. Although the behavior was "brittle," as a large deformation did not appear before the collapse, the dome held its structural stability, considering the warm condition. Clearly, it was the spring weather that lowered the quality of the ice plate and

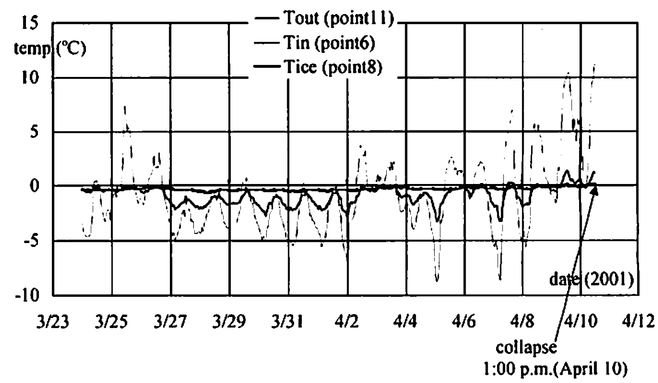

Fig. 21 Temperature-time curve before collapse

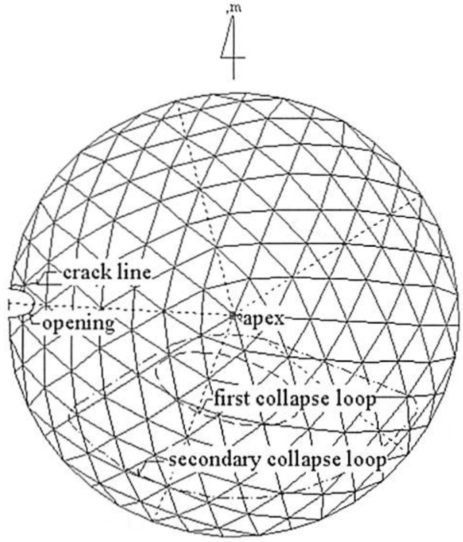

Fig. 22 Behavior of collapse

led to the brittle failure of the structure in this case. It is advisable to spray water and blow snow onto the dome several times even after its completion, as an easy means of maintaining the ice quality, thus improving the structural safety of the ice dome. It can be concluded that this size of ice dome will be applicable as an architectural structure during the winter season in Tomamu. A very important question is whether a 30-m-span ice dome with good-quality ice results in the brittle behavior of collapse or not. Fig. 22 shows the sequential order of the collapse. The first collapse occurred in the middle of the south side, where the sun shone strongest over the dome. The crack beside the opening of the dome did not spread enough to affect the structural behavior. Fig. 23 shows the exterior view after the second collapse.

Fig. 23 Exterior view right after collapse

CONCLUSION

As a result of these experiments, we are led to the conclusion that an ice dome spanning 20~30 m could be used as an architectural structure. This construction method of blowing snow and spraying water onto an air-inflated membrane as formwork is very practical for a large ice shell, because it needed only 6 days to complete, despite the considerable size.

Considering the actual construction equipment such as the snow-blower and the adjustable nozzle for spraying water, the size of the ice dome may be limited, for now, to a 30-m span. However, it would be possible to construct a 40-m-span ice dome if the equipment were available. The Pantheon in Rome, constructed in about 120 A.D. and well known as one of the biggest, classical stone domes, has a base diameter of about 40 m. Ice is easier to manufacture than stone, and its strength/density is greater than stone in short-term loading, so it should be structurally possible to realize a dome of this size in ice as well as stone. On the other hand, ice is a translucent material, so the ice shell creates a fantastic, beautiful space providing quite a unique built environment in winter. Particularly in the case of a large span, it will be more impressive aesthetically and more useful for application to various kinds of architectural facilities.

An ice dome spanning 20~30 m is a large ice shell of unprecedented size, so its structural behaviors and reliability are not fully known, even though this experiment was successful during the period of intended use. Toward the realization of the 20~30m-span ice dome for architectural structure, much more continued research concerning the reliability of its structural safety and the improvement of the construction technique will be needed to continue in the future.

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