RE-CHALLENGE TO 20-M SPAN ICE DOME

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ABSTRACT
A large ice shell with spans from 20 m to 30 m has not yet been utilized as an architectural structure for lack of the reliability on its construction technique and structural safety. This paper describes the construction experiment and creep behavior of the year 2000' test-dome, and concludes, that a 20-m span ice dome is possible to use as an architectural structure during winter in Tomamu, Hokkaido.

1.INTRODUCTION

Aiming at the production of ice shells with spans from 20 m to 30 m, which could be used for a variety of winter structure in snowy and cold region, we started the study of structural and constructional engineering aspects at the beginning of 1980's. Concerning to the structural safety and the construction technique, the theoretical and experimental studies had been carried out [1-7]. On the other side, concerning to the application of ice shell, 10-m span small ice domes had been practically used for a variety of temporary shelters such as a winter storage of vegetables, a factory house for making Japanese "sake" and a working space at the basement-area for Japan Observatory in the South-Pole [8].
The results of these studies provided the opportunity never experienced before to construct ice shells for an architectural space in Tomamu, Hokkaido since 1997. Many ice shells have been used as leisure spaces for tourists about 3 months in each winter and these have created a fantastic, beautiful space providing quite a unique built environment in winter [9]. 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, a large ice shell with spans from 20 m to 30 m might be possible to use as an architectural structure. But, the actual proof test of the large ice shell had not been experienced before except the field experiment of 20 m span ice dome in 1985. Because of the lack of the actual experience so far, the confidence of its structural reliability to use for architectural facility is not enough.
Therefore, toward the reliability of its structural safety and improvement of the construction technique, 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 year 1999 and 2000. These test-domes had shown a high structural efficiency compared with the first test-dome constructed in 1985 that had geometrical and material imperfections because of unskilled snow blowing operation.
This paper describes the construction and creep test of the year 2000' test-dome, and concludes, that the realization of 20-m span ice dome is possible to use as an architectural structure during winter in Hokkaido.

2. CONSTRUCTION

2.1 Snow-Ice Foundation Ring

It needed about half a day, February 3rd in 2000, for the construction of the snow-ice foundation ring. The ring was constructed by pouring snow and water into a mould made of veneers, and treading down so as to harden and freeze the snow-ice sherbet. It had about 17 m in inner diameter, 90 cm in depth and 1 m in width, so the total weight became about 40 tons if $0.85 g/cm^3$ was evaluated as the density of the snow-ice. Therefore, it was judged that the ring was heavy enough against the lifting force 15 tons under the inflation of pneumatic membrane as formwork.

2.2 Air-Inflated Membrane

The P.V.C. bag was inflated in the afternoon of February 4th. The bag was the same membrane for 1985' dome and had 20 m in diameter, 350 kg in weight. The net was laid on the membrane and connected to the end ropes anchored in the foundation ring. As shown in Fig.1, 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 between points was all the same 1.5 m, supposing the rise of dome 6.2 m. A portable blower, which has a capacity of airflow 44 m^3/min. and maximum water head 46 mm aq., was used for the inflation. As the theoretical results, it was assumed that the inflation time was within about 30 minutes and the rope was strong enough. After the inflation in Fig.2, about 20 pieces of Styrofoam sticks for checking the shell thickness under the construction were located on the membrane.

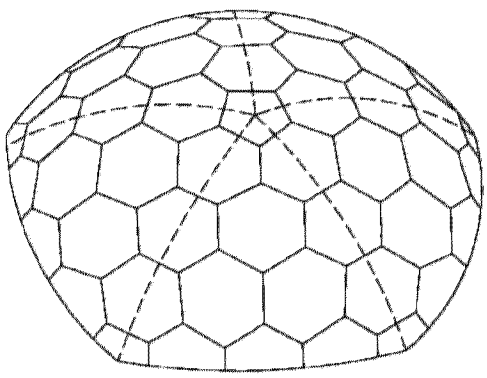

Fig.1 Reticulated pattern by geodesic division

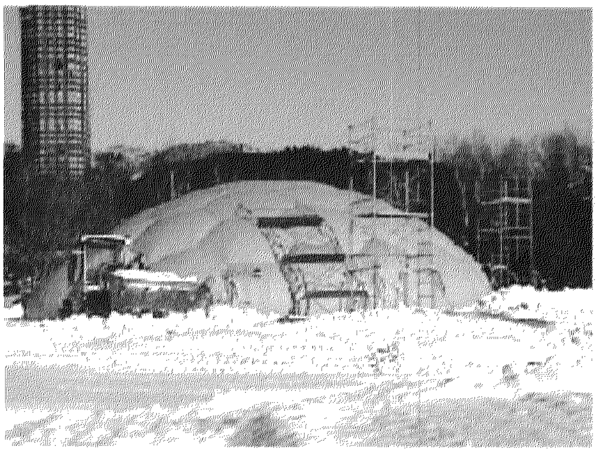

Fig.2 Air-inflated membrane as formwork

2.3 Application of Snow and Water

Before the application of snow and water onto the membrane, snow and water were prepared so as to transmit smoothly forces between the periphery of the shell and the foundation. As reported in the preceding paper [6], geometrical and material imperfections of the constructed 1985' dome were observed because of the unskilled snow blowing operation, and the structural efficiency was very low as the result. In order to keep the snow thickness less than 1 cm during one operation, the milled snow was carefully blown onto the membrane by a rotary snow plow with the maximum throwing distance 22 m, and tap water was continuously sprayed on the snow by 6 adjustable nozzles with the maximum spraying distance of 15 m and the spraying amount of 60 litter/minute in total. The spraying water onto the vicinity of apex was done by standing on a high stage. Fig.3 shows the outside air temperature during construction, and as shown in Fig.4, the dome looked like a 'steaming giant bean-jam bun' when outside air temperature was below –13 ℃ and sky was clear.

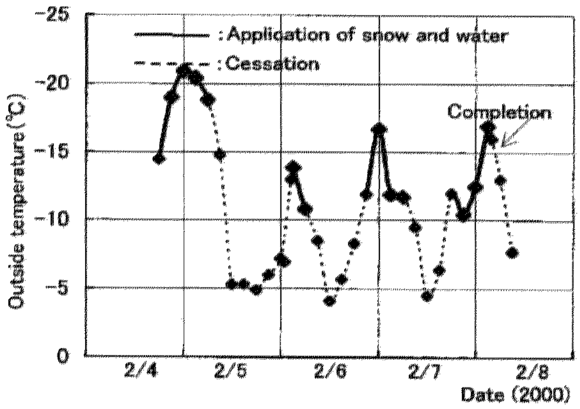

Fig.3 Outside temperature under construction

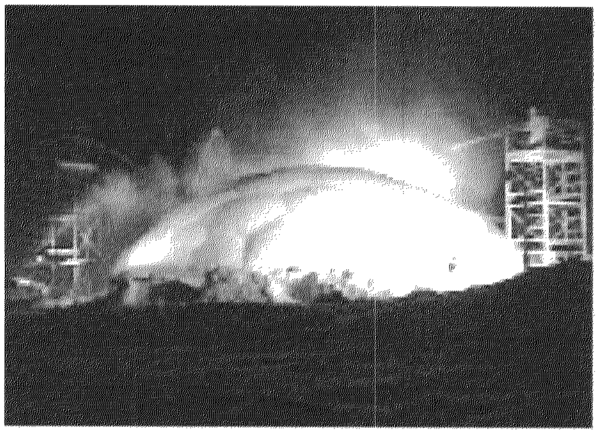

Fig.4 Steaming giant bean-jam bun

2.4 Deflation

It was 4 a.m. on February 8th when the application of snow and water was finished and then the membrane started immediately to deflate. The inside space was quite huge compared with human scale and gave a feeling of space never experienced before. Fig.5 shows the situation of removing the membrane after deflation.

Fig.5 Removing membrane

3. DESCRIPTION OF DOME MODEL

The completed dome was assumed to have the geometry of a spherical surface. Based upon the measure of the height at the top points and the inner diameter at the base, the radius of curvature and base diameter were computed as 1040 cm and 1720 cm, respectively. Fig.6 shows the shell thickness at the major points, and the distribution was fairly scattered because the frozen Styrofoam sticks with scale were not useful for reading the shell thickness under construction. The designed shell thickness was 15 cm at the top, 17.5 cm at the middle part and 20 cm at the bottom, but the result showed 12.5 cm, 17.9 cm and 18.4 cm in average respectively. The thickness was comparatively thin at the bottom because of the steep slope. It took 2 hours to get 1 cm thickness in this construction because it needed 36 hours in total to attain the average thickness 17.9 cm as shown in Fig.3 and 6.

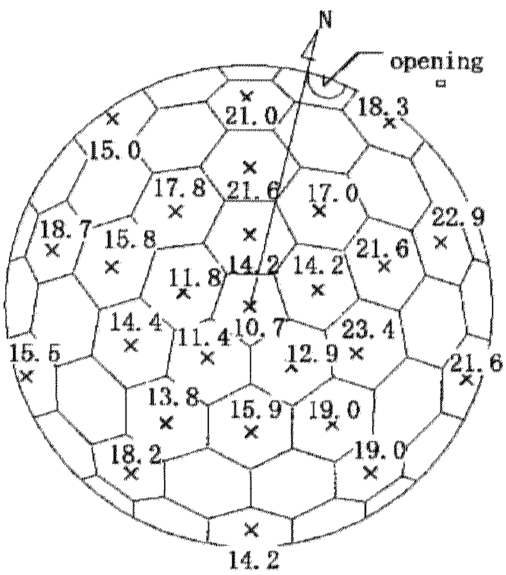

Fig.6 Ice thickness (cm)

4. CREEP TEST

4.1 Outline

Displacements and temperatures were automatically measured from February 12th to March 27th. As shown in Fig.7, 21 points for measuring vertical displacements were prepared at the inside surface of the test dome. The hanging method was adopted to easily measure these displacements, which were recorded automatically by a programmable data logger at intervals 3 hours. 5 points for measuring temperatures are shown in the same Fig.7. One point of outside, two inside, and two ice temperatures were measured by self-recorded thermometer at interval 1 hour. Furthermore, in order to get the information of the snow load on the test dome during the creep test, the variation of the snow depth as shown in Fig.8, was observed by a box scale apart from the dome. The increase of snow depth from the beginning to March 24th was about 20cm, and it means that the snow load did not practically influence upon the creep behavior of the dome even if the snowdrift was considered. After the automatic measurement, all displacement transducers and some thermometers were removed and the structural behavior was observed by eye up to the collapse.

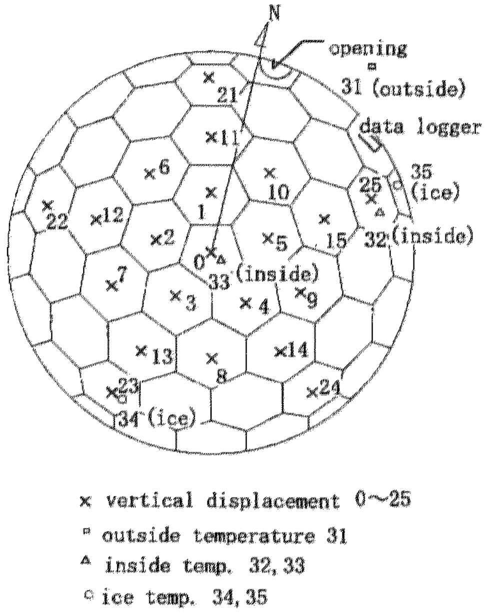

Fig.7 Points for disp. and temperature

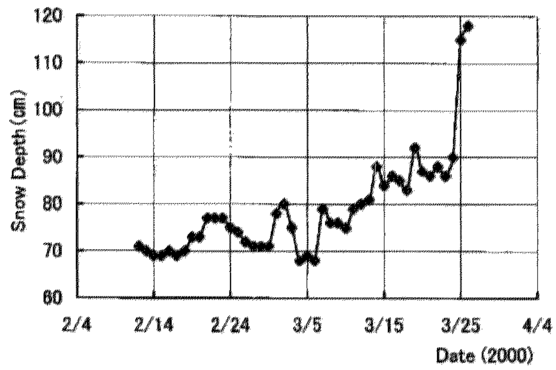

Fig.8 Snow depth-time curve

4.2Results and Discussions

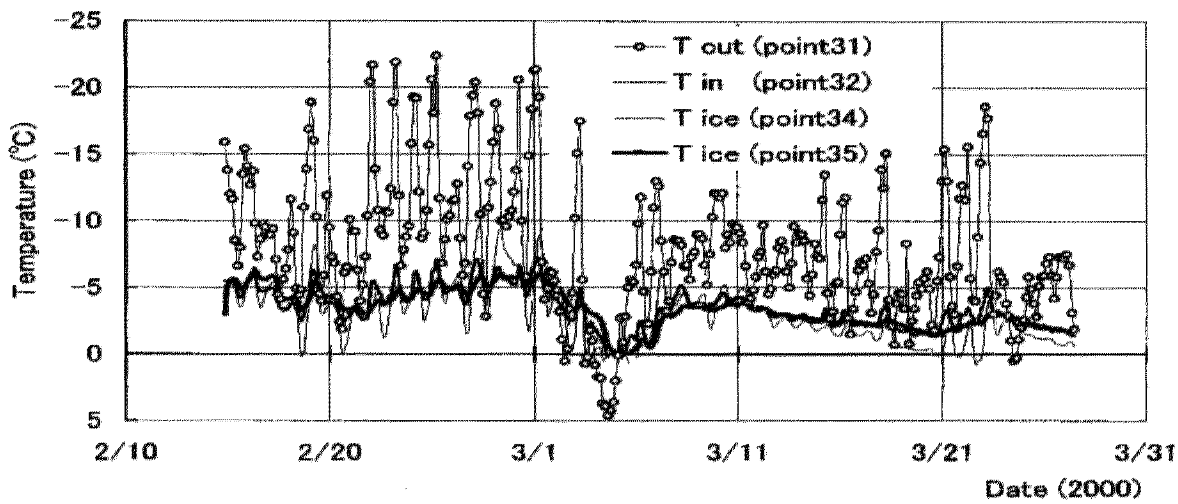

Fig.9 Temperature-time curves

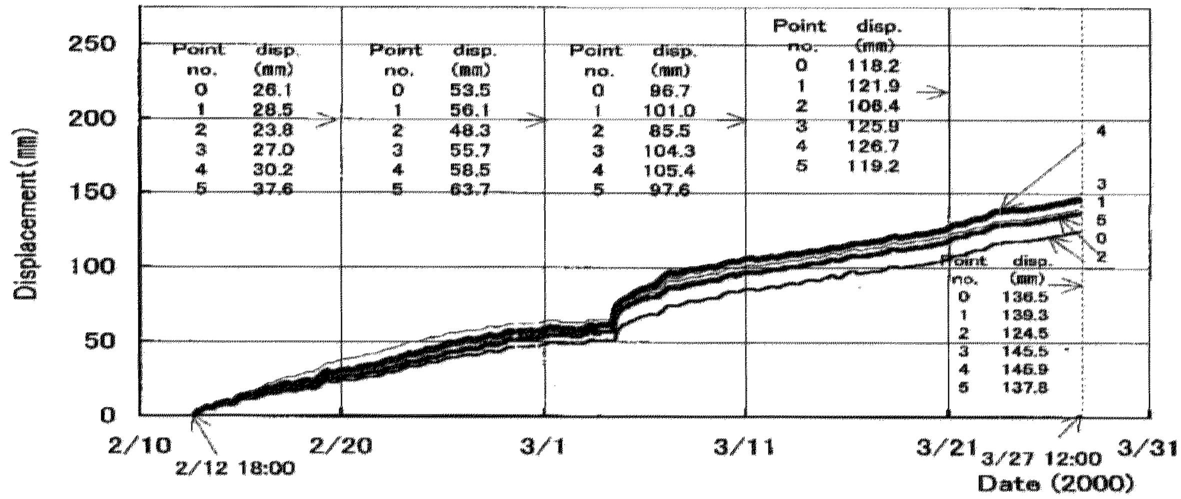

Fig.10a $\delta_{0\sim5}$-time curves

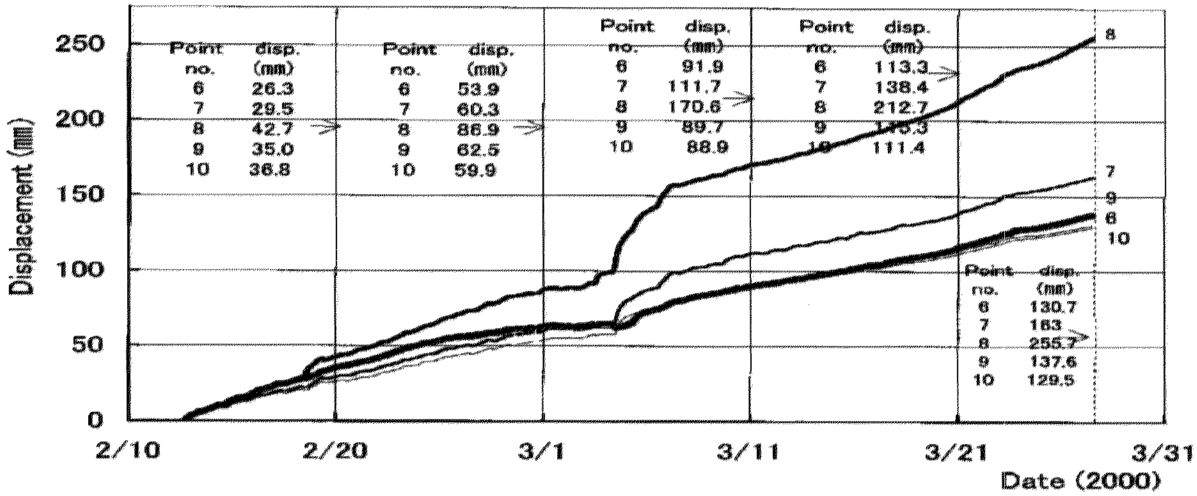

Fig.10b $\delta_{6\sim10}$-time curves

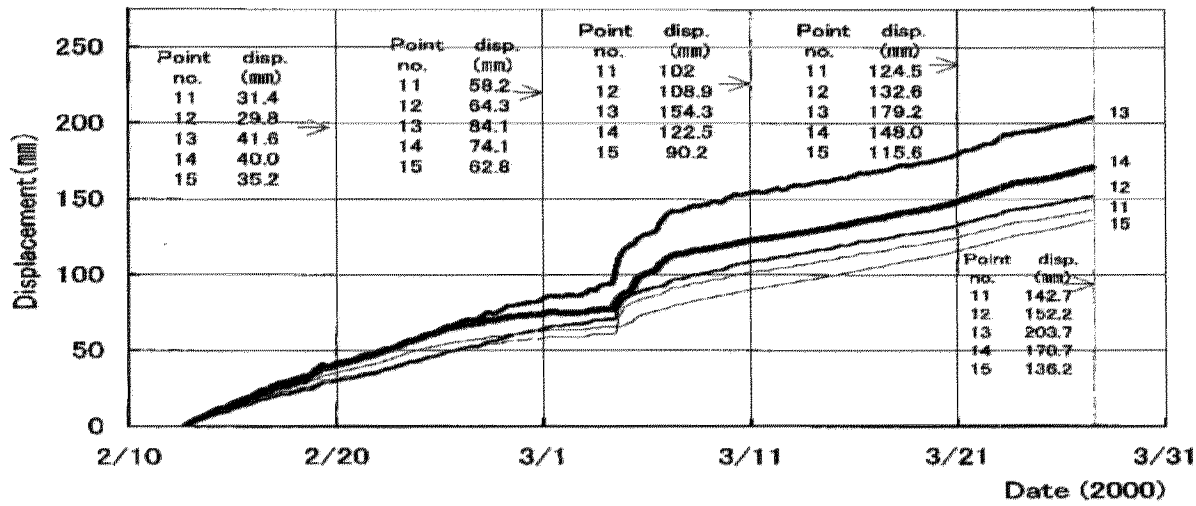

Fig.10c $\delta_{11\sim15}$-time curves

Fig. 9 and Fig.10a-c show temperature-time curves and displacement-time curves, respectively during the whole period. In these Figs., the most noteworthy point is that the deformation from March 4th to 6th dramatically increased. As shown in Fig.11a, the ice

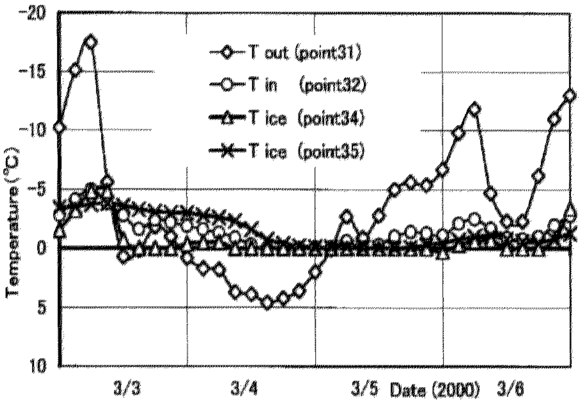

Fig.11a Temp.-time curves (3/3-3/6)

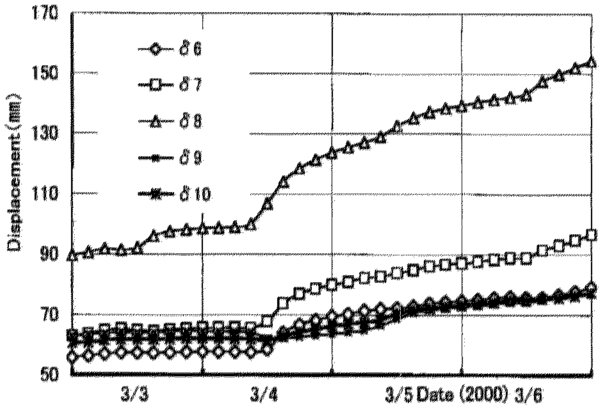

Fig.11b Disp.-time curves (3/3-3/6)

Table 1a Average temperature(℃)

Point no.	2/14～2/29	3/11～3/26	3/4～3/7	whole(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 1b Average creep displacement(mm/day)

Points no.	2/14～2/29	3/11～3/26	3/4～3/7	whole(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

temperatures whole the dome constantly kept 0℃ in this period because of warm air and strong sunlight at the beginning of Spring. Fig.11b shows the displacements started to increase abruptly at the noon March 4th when Tice (point35) reached to just 0℃. One column of Table 1 quantitatively shows the temperatures and displacements in this period (3/4～3/7), and it was supposed that the almost 0℃ ice temperature gave rise to a sudden increase of deformation. Except this period, as shown in Table 1b, the structural behavior of the dome was stationary although $\delta_{8,13}$ at the south side were larger than the other δ . According to the comparison of the results between the before and after of 3/4-3/7 as written in Table 1b, displacements during the before period, 2/14-2/29, in spite of its more severe physical condition as shown in Table 1a,were larger than the after period, 3/11-3/26, except δ_8. In this test, displacements sometimes decreased according to a rise of ice temperature. Fig.12 shows the typical example of temperature, displacement-time curves. The reason is described as follows. Decreases in $\delta_{1,2,3,4}$ during 9:00-12:00 February 19th, were 0.9 mm, 1.0 mm, 1.4

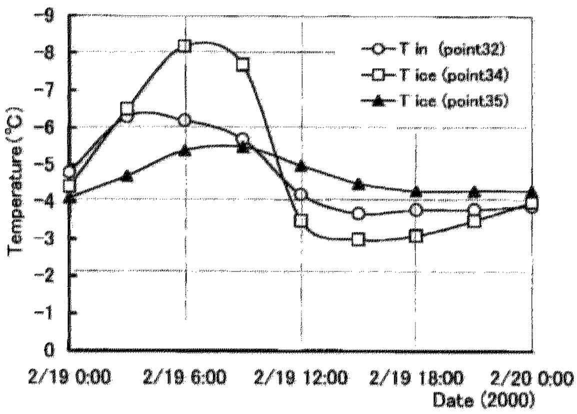

Fig.12a Temp.-time curves (2/19)

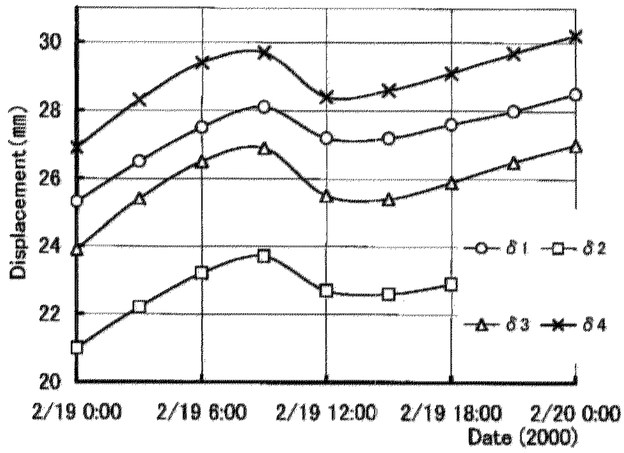

Fig.12b Disp.-time curves (2/19)

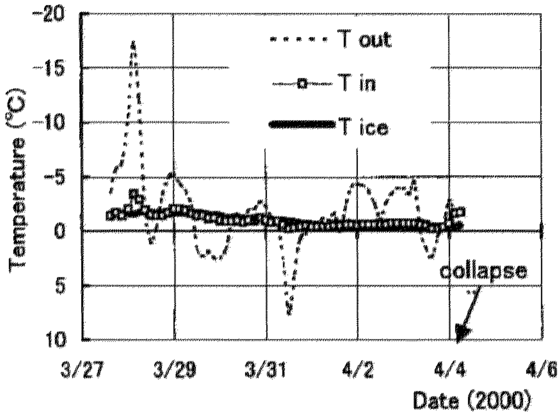

Fig.13 Temperature before collapse

Fig.14 Large deformation onset collapse

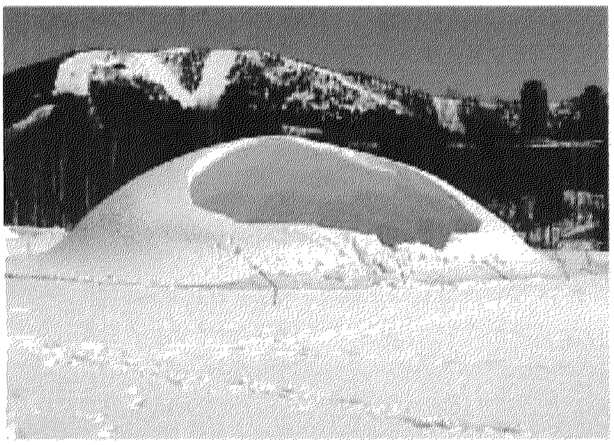

Fig.15 Scene just after collapse

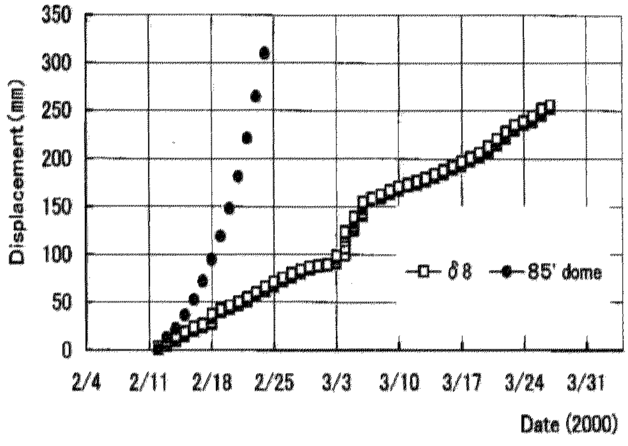

Fig.16 Comparison between 00' and 85' dome

mm and 1.3 mm, respectively, and the average was 1.15 mm. Referring to Table 1b, the average creep displacement in this period(2/14~2/29) was 0.375 mm per 3 hours. If 5×10^{-5} /deg was evaluated as the coefficient of thermal expansion of the ice and 10400 mm was used as its radius of curvature, 0.52 mm/deg was computed as the decrease in displacement and 2.9 deg was needed as the temperature difference corresponding to the decrease in displacement

1.525(=1.15+0.375) mm. Differences in Tice(point34) and Tice(35) were 4.2 deg and 0.5 deg, respectively during the intervals. Therefore, it is interpreted the thermal expansion of ice brought the decrease in displacement. After removing the displacement transducers on March 27th, the structural behavior was observed bye eye up to the collapse on April 4th. Fig.13 shows the temperatures during the period. Because of the absence at the site from March 31st to April 1st, it was April 2nd when the large deformation was firstly observed. So, it was difficult to guess when the large deformation started. On the noon of April 3rd, a large depression with about 8 m in diameter and about 2 m in depth was observed from the outside of the test-dome, as shown in Fig.14. The dome was escaped from the collapse until next morning, and it was as ductile as the preceding experiments. Fig.15 shows the scene just after the collapse of the dome. 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 at several times during its application, as an easy method for keeping the quality of ice which means improvement of the structural safety of the ice dome. Fig.16 shows 2000' dome had a high structural efficiency compared with the 1985' dome that had geometrical and material imperfections.

5. CONCLUSION

This paper described the field study of the 20-m span ice dome carried out in 2000. The results show a 20-m span ice dome is fundamentally possible to use for architectural facility such as a multi-purpose hall for winter event though following points need further study.

1) Concerning to construction technique: a) Investigation on the thermal process to produce the ice by blowing snow and spraying water. b) Devices for measuring ice thickness and making ice at steep part of shell under construction.
2) Concerning to structural safety: a) Understanding creep property of the ice under almost 0℃ ice temperature and low stress 0.5～1 kg/cm^2. b) Effect of geometrical imperfection along the ropes on the structural behavior.

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