IAHR Ice Symposium 1988
Sapporo

CONSTRUCTION AND CREEP TEST OF 15-M SPAN ICE DOME

Tsutomu Kokawa
Professor Dr.-Eng.

Department of Architecture,
Faculty of Art and Technology,
Hokkaido Tokai University
Japan

A field study on both the construction and creep test of a 15-m span and 3.3-m rise ice dome was carried out at Hokkaido Tokai University in Asahikawa during the winter of 1986.

The dome was constructed by the following method which satisfies fundamentally the facility of a rapid, easy and economical construction. Inflating a membrane bag covered with ropes anchored to the snow-ice circular foundation ring. Covering the membrane with thin snow-ice sherbet by blowing the milled snow with a rotary snow-plow and spraying tap water with a high pressure adjustable nozzle. Solidifying the snow-ice sherbet due to cooling by cold outside air. Repeating the application of snow and water up to the desired shell thickness. Then removing the bag and ropes for reuse. The completed dome had a good quality of ice and the inside light sufficiently transmitted through the dome.

After construction, a creep test was carried out under snow load, and the structural behaviour up to the collapse was examined. as the results, the central displacement rate at the secondary creep stage was about 1.5 mm/day, its lifespan was from January 15 to April 3, and it was shown that the dome had good enough structural efficiency.

Based on thh result of this study, the production of a large span ice shell could be practicable.

INTRODUCTION

Ice shells are a new type of ice structures based on the modern structural engineering and may create an architectural space in the snowy and cold regions.

On account of both the easy construction technique and high durability, 10-m span ice domes have been recently used for the winter storages of vegetables and Japanese "sake" as shown in Fig.1 and 2, at the northern parts of Hokkaido in Japan.

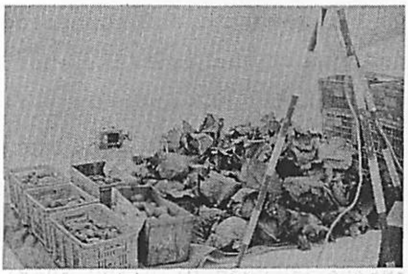


Fig.1. Storage of vegetable

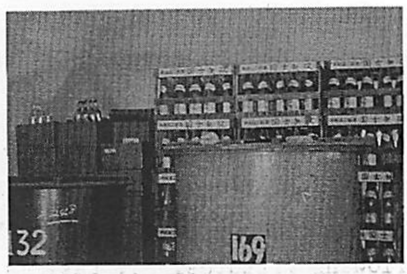


Fig.2. Storage of sake

20-30 m span ice shells which could be used for sport-leisure centers and festival halls, have good enough durability theoretically. However, the construction of a 20-m span ice dome carried out before (Kokawa and Murakami,1986), was not so good because too much milled snow was blown onto the membrane during one blowing operation by the snow-plow.

Now, reducing the size, a 15-m span and 3.3-m rise ice dome was carefully constructed, and had a good quality of ice. According to the subsequent creep test, its lifespan was from January 15 to April 3 and the dome had good enough structural durability.

CONSTRUCTION

Construction Method

Polypropylen ropes with 12 mm diameter are lashed to the log timbers interbedded with the snow-ice foundation ring. The ring with 15 m central diameter and 45 cm × 130 cm section, is constructed by pouring snow and water into a mould made of veneers as shown in Fig.3, and treading down so as to harden and freeze the snow-ice sherbet promptly.

A PVC membrane bag is placed on the snow ground as shown in Fig.4. This membrane bag is fabricated by welder along the periphery after wrapping in two pieces of plane sheets with 15 m diameter.

Fig.3. Foundation work

Fig.4. Placing membrane on the snow ground

Each ropes are laid orthogonally on the membrane and connected at the center by the turnbuckles which can adjust the initial length. Rope spacing in each direction is 1.65 m.

After inflating the bag in a short time by a sirocco fan, the inner pressure is held at 7 cm water head by a voltex blower with a pressure controlling machine. Fig.5 shows the air-inflated formwork which has following features: 1. Easy manufacturing because of plane sheets. 2. Easy control of inner pressure because of slight air leak. 3. High rigidity and strength by producing the local curvature.

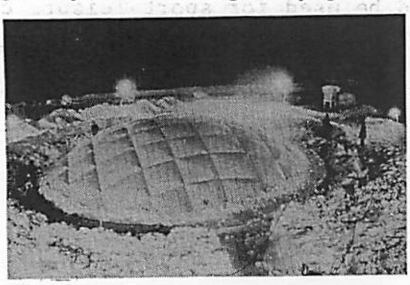


Fig.5. Air-inflated membrane as formwork

Fig.6. Snow blowing by rotary snow-plow

The space between the periphery of the membrane and the foundation is filled with snow. Snow is blown onto the membrane by a rotary snow-plow and tap water is sprayed on the snow by a high pressure adjustable nozzle, as shown in Fig.6 and 7. As a result of this operation, a snow-ice sherbet is produced on the membrane, and it is frozen hard some time later under the conditions that air temperature is below -10 °C. Fig.8 shows air temperature under construction. It is necessary during one blowing operation to keep the milled snow depth to be thin. If not so, when water is sprayed, only the surface solidify and the membrane cannot keep the form because of the excessive weight which cause material and geometrical imperfections as before-reported (Kokawa,

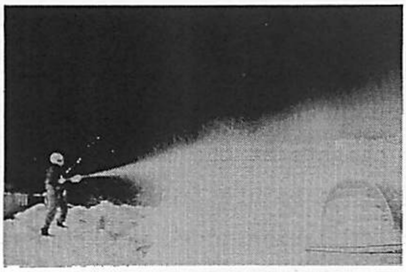


Fig.7. Water spraying by high pressure nozzle

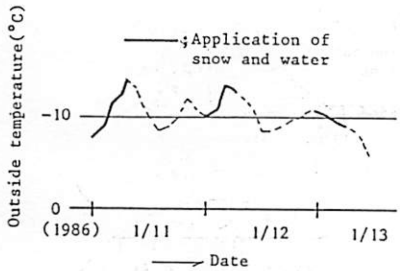


Fig.8. Outside air temperature under construction

and Murakami,1986). The snow-ice sherbet solidify more quickly than only water because of the low latent heat, and the ice seems to be more ductile material. When the thickness of the ice plate reaches to amount, the ice can support the weight of new snow-ice sherbet layer instead of the inflated membrane. Therefore, the membrane do not need a high pressure and the formwork including the foundation ring becomes lightness and low cost. The application of snow and water are repeated up to the design shell thickness which is about 1/100 th of the span. It took 20 hours to get 15 cm average thickness in this test.

The membrane bag is deflated as shown in Fig.9, and the ropes and bag for reuse are removed. The ice dome is then complete, as shown in Fig.10 and 11. The completed dome had a good quality of ice and the

Fig.9. Deflated membrane

Fig.10. Completed dome

Fig.11. Inside view

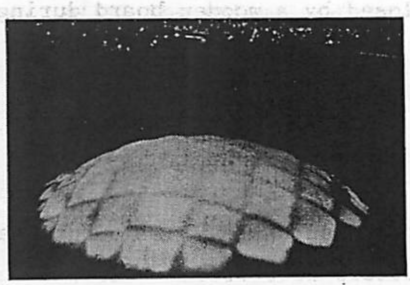
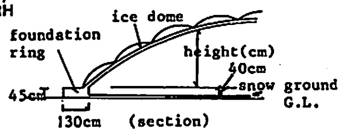


Fig.12. Dome at night



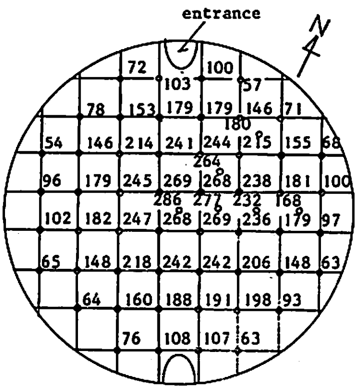


Fig.13. Height(cm) at major points

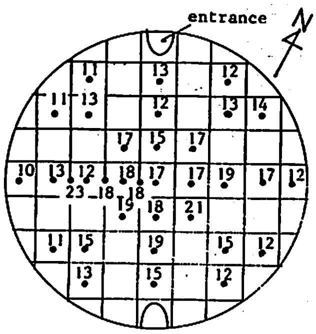


Fig.14. Thickness(cm) at major points

inside light sufficiently transmitted through the dome, as shown in Fig.12.

Geometry of Ice Dome

The heights at the major inside ropes intersecting points from the upper level of the foundation ring, were measured by a transit instrument, as shown in Fig.13. And the height from the upper level to the snow ground, was about 40 cm.

Judging from these results and inside span (=13.7 m), it was assumed that the dome had almost spherical shape and its radius of inside surface was about 9.86 m by means of least-squares fitting.

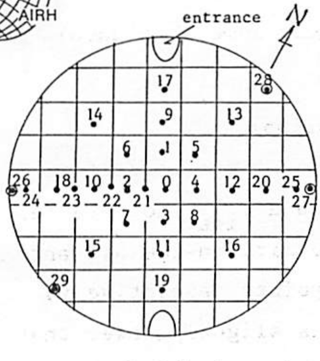
Fig.14 shows the observed shell thickness. The snow blowing technique needs a very good skill, and it was difficult to get a desired shell thickness inspite of putting a guide-stick on the membrane before the application of snow and water. The shell thickness distribution had a tendency to be a little thick at the central part and the rope location. Accepting the dispersion, the average thickness was about 14.5 cm.

The entrance had a half ellipse with 1.3 m wide and 1.25 m high, and its edge was stiffened with ice arch-beam. Two entrances were normally closed by a wooden board during the creep test.

CREEP TEST

Test Method

30 points for measuring displacements and 10 points for strains were prepaired at the inside surface of the test dome. The displacement transducers were used for measuring displacements. The displacements of point Nos. 0 to 25 indicate vertical displacement, and that of point Nos. 26 to 29 indicate normal displacement as shown in Fig.15. The hanging



● ; vertical displacement (nos. 0-25)

◉ ; normal displacement (nos. 26-29)

Fig.15. Numbering points for measuring displacement

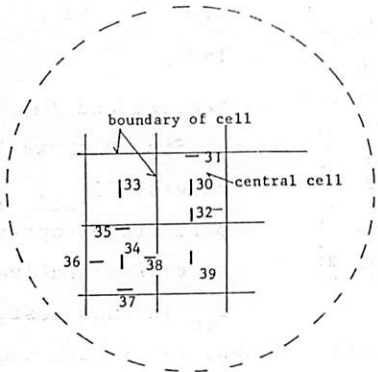
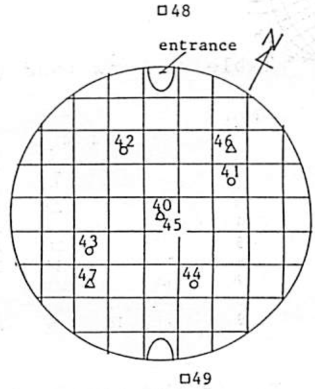


Fig.16. Numbering points for measuring strain



o ; ice temperature

△ ; inside temperature

□ ; outside temperature

Fig.17. Numbering points for measuring temperature

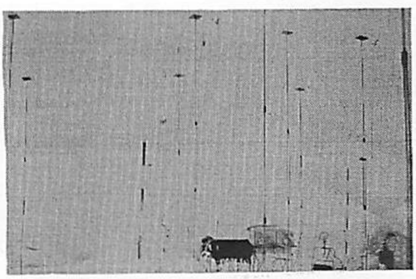


Fig.18. Inside view under creep test

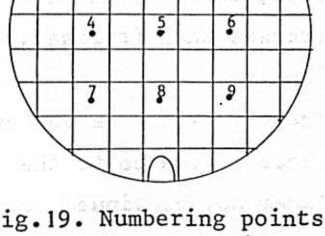


Fig.19. Numbering points for measuring snow depth

method(Kokawa,1985) was adopted so as to measure easily the vertical displacement.

π-type gauges were used for measuring strains, as shown in Fig.16.

Fig.17 shows ten points for measuring temperatures. Two points outside, three inside and five ice temperatures were measured by copper-constantan thermocouples.

All displacements, strains and temperatures were recorded automatically by a programmable data logger with 4 hours intervals from Fanuary 21 to March 19 as shown in Fig.18, exclusive of February 28 to March 5 when the data logger had gone wrong. After the automatical measurement, the structural behaviour was observed by eye up to the collapse.

Dead load and snowfall load had been acting to the test dome. The snow load was estimated by snow depth on the dome and the density on the ground. Fig.19 and Table 1 show the snow loads at several time during the test. It was recognized the seasonal west wind blows

Table 1. Snow load (kg/m^2)

Point No.	2/1	2/2	2/14	3/6	3/26
	Date (1986)				
1	26	5	27	28	30
2	20	0	24	35	57
3	11	0	23	16	54
4	15	0	23	23	15
5	17	0	20	25	42
6	20	0	23	25	78
7	18	2	21	9	6
8	20	0	17	9	21
9	41	18	36	39	99

snow into pile on the dome than usual year.

Results and Discussions

Fig.20 shows three temperature-time curves. T_{out}, T_{in} and T_{ice} indicate temperature of outside air, inside air and ice at representative points respectively.

T_{in} in this test, is slightly lower than T_{in} in the previous test (Kokawa,1985;Kokawa and Murakami,1986), because the snow at the central part was swept out by the frequent west wind. When two entrances were opened at the same time, T_{in} was lower than T_{ice}, as shown in Fig.20.

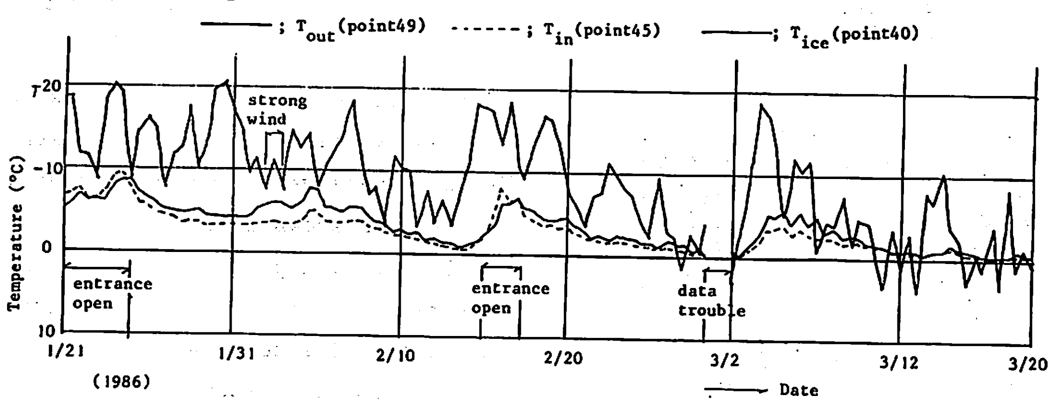


Fig.20. Temperature-time curves

Fig.21 shows displacement-time curves, where $\bar{\delta}_{i,j,k,l}$ means average displacement at measuring point Nos. i,j,k,l. As mentioned before, the data logger occured a mechanical trouble from February 28 to March 5.

After repairing the logger, the data were recorded again from zoro set. Before or after January 25, February 5 and 16, the vertical displacement rate increases when T_{ice} falls and decreases when it rises. It seems to be due to the thermal expansion of the ice.

Taking a broad view, the deformation grows linearly with time during from the beginning to nearly March 10, and then accelerates up to the collapse. $\bar{\delta}_{26,29}$ which is average normal displacement, continued to decrease slightly from January 25 to March 12.

In order to grasp the creep coefficient η obeyed to Eq.(1), the linear analysis was carried out by thin shell theory developed at the previous paper (Kokawa,1984).

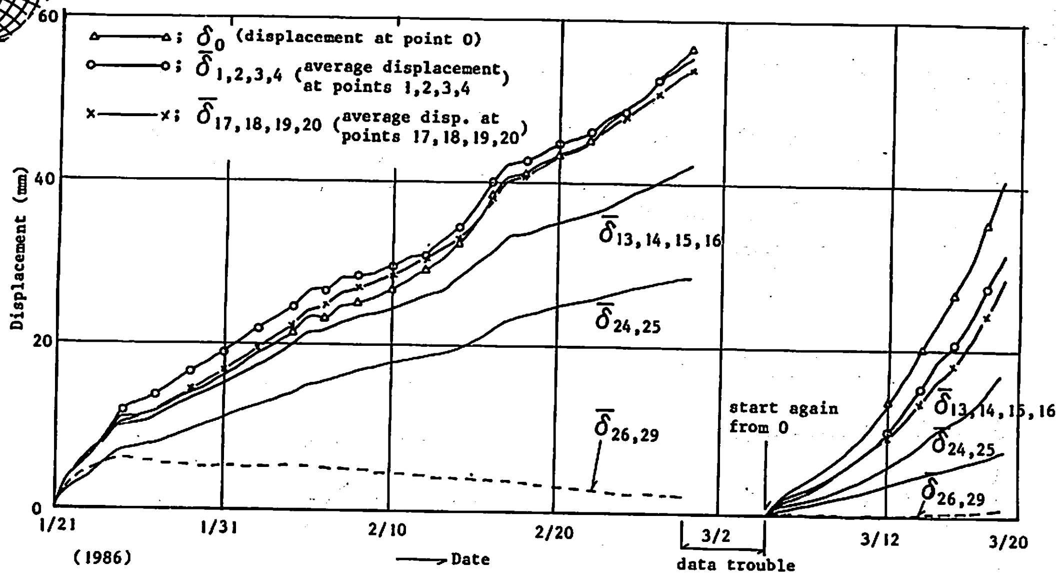


Fig.21. Displacement-time curves

$$\dot{\varepsilon} = \eta\sigma \qquad (1)$$

Where $\dot{\varepsilon}$, η and σ are strain rate, creep coefficient and stress, under uniaxial compression. The following mathematical model was used. The average thickness is 14.5 cm, the radius and open angle of the dome is 9.86 m and 88 degrees, respectively. The sectional area of the foundation ring is 0.585 m^2(45cm×130cm). The vertical uniformly load is 150 kg/m^2. As a result of this analysis, there exists the following relation between the creep cpefficient η and the displacement at the center $\Delta\delta_0$

$$\eta = 1.02\cdot10^{-9}\times\Delta\delta_0 \quad (cm^2/kg\ sec^{-1}) \qquad (2)$$

(mm/day). As shown in Fig.22, $\Delta\delta_0$ is 1.25 (mm/day) in case of January 30 to February 3. So, η becomes $1.28\times10^{-9}(cm^2/kg\ sec^{-1})$.

Fig.23 shows three strain-time curves at the central cell on the dome. From this Fig., strains at point 30,31 are in compression, and ε_{32} is in tension by the bending moment perpendicular to the boundary line of the cell. These results are qualitatively same as finite element analysis. Because the boundary of each cell is not sufficiently stiffened in this dome, i.e., the sectional area is somewhat small, the relatively big bending stress occurs near the boundary.

Although T_{out} often rose to more than 0 °C every days after March 20, as shown in Fig.24, the dome did not collapse immediately. In fact, it was April 3 when the dome collapsed. Snow cover makes the ice dome

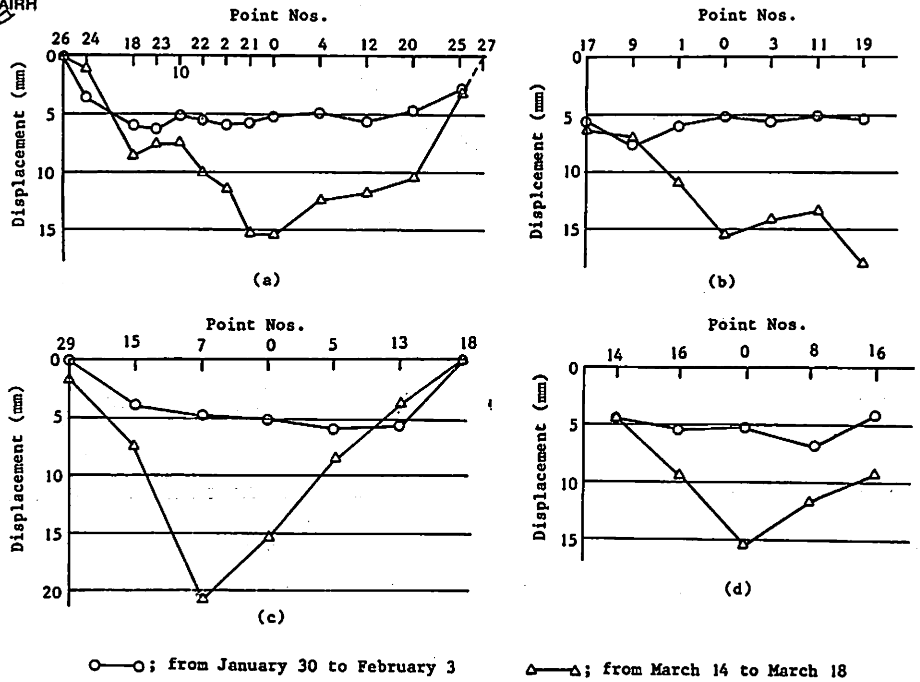


Fig.22. Incremental deformation during four days along each direction

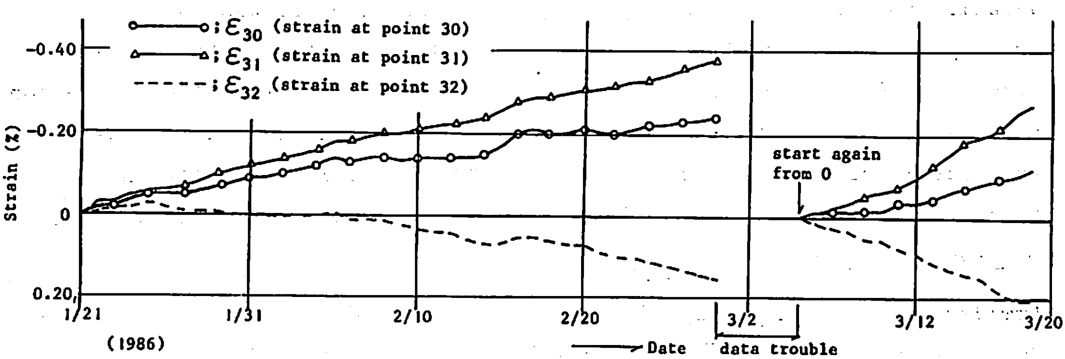


Fig.23. Strain-time curves

keep long, because of its high thermal insulation effect.

The central deformation accelerates gradually with time from March 10, as shown in Fig.21. At this stage, the regions near point Nos. 0, 7,19 considerably deform, as shown in Fig.22. For example, the displacement rate at point No.7 is 5 mm/day from March 14 to March 18. It is considered that this is due to the increase of η by rising T_{ice}, the increase in snow load and the geometrical nonlinearity. On the other side, the displacement rate near the dome boundary did not vary with time.

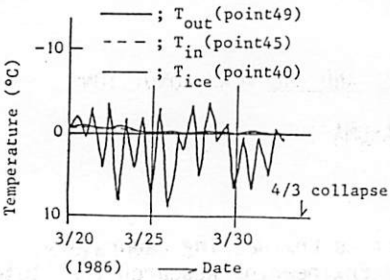


Fig.24. Temperature-time curves after March 20

Fig.25. Deformation at onset of collapse

After the automatical measurement, the structural behaviour was observed by eye up to the collapse. At the onset of the collapse, it was guessed that the central deformation was about more than 100 cm, as shown in Fig.25. It indicates that the ice shell is very ductile, in other words, the collapse does not occur abruptly, and we have enough time to predict the danger of collapse.

CONCLUSION

Snow and cold realized ice shell. Based on the results of this study and previous investigations, the production of a large span ice shell could be practicable. When the structural reliability will be gained much more by the untiring studies, it may be a new spatial structure in the snowy and cold regions.

ACKNOWLEDGEMENT

The author thanks to seventeen students of Hokkaidò Tokai University who constructed the 15-m span ice dome with him.

REFERENCES

Kokawa,T., 1984. Axisymmetric creep buckling analysis of ice dome. (in Japanese) Bull.Hokkaido Tokai Univ., 5:17-24.

Kokawa,T., 1985. Experimental studies on ice shells in Asahikawa. Cold Regions Science and Technology, 11, 155-170.

Kokawa,T. and Murakami,K., 1986. Challenge to 20-m span ice dome. Shells, Membranes and Space Frames, Proceeding IASS Symposium, Osaka, Vol.1, 297-304.