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A Field Study on 10m-Span Ice Shell*

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スパン10メートル・アイスシェルのフィールド実験

粉川　牧

1983－1984の冬期間，スパン10mモデルを用いてアイスシェルの建設施工法とクリープに対する構造安全性についてフィールド実験を行った．建設は(1)，雪氷基礎リングの施工，(2)二重平面膜と押さえロープからなる型枠空気膜構造のインフレーション，(3)所定の板厚（スパンの1／100強）となる迄，散雪散水及び凍結硬化の繰り返し作業，(4)デフレートの手順によった．試作後，自重及び雪荷重のもとで，クリープ実験が行われ，変位，温度を測定し，崩壊迄の力学的挙動を検討した．今回の実験で，本建設方法によって基本的に迅速，簡易且つ低コストでアイスシェル建設が可能であること，一方崩壊日数が約3ヵ月と充分な力学性能を有していることが実証され，これらの結果から，スパン20－30m級の実大規模のアイスシェル建設が技術的に充分可能であることが示唆された．

ABSTRACT

This paper describes a field study on both the construction technique and the creep test of a 10-m span ice dome. Construction technique consists of : 1. inflating a membrane bag covered with rope, 2. spraying it with snow and water, 3. solidifying the snow-ice sherbet on it, 4. removing the bag and rope for reuse. Subsequently, a creep test was carried out under snow load, and its structural behaviour up to collapse was examined.

1. INTRODUCTION

Asahikawa is located at the center of Hokkaido in Japan. The physical environment of Asahikawa district becomes severe in winter. According to meteorological data for the past thirty years (Sapporo Meteorological Agency, 1982), the average air temperature in January and February is about －8℃, the yearly total number of ice days is 80, and the yearly mean maximum snow depth is 90cm. The author had been studying from the view point of structural engineering, the production of ice shells with spans 20 to 30m in this environment (Kokawa and Hirasawa, 1983a ; Kokawa, 1983b, 1983c, 1984b, 1984c, 1985 ; Hirasawa and Kokawa, 1984a). The ice shell is thin, and its structural material is snow-ice. The ice shell may be, so to speak, a contemporary "igloo" or "kamakura". It may be an efficient

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method for providing shelter in snowy and cold regions. How do we construct the ice shell rapidly, easily and economically ? How about its structural safety ? In a preceding paper (Kokawa, 1985), the study on creep buckling collapse of a 5-m span ice dome was described.

This paper contains the field study on both the construction technique and the creep test of a 10-m span ice dome performed at Hokkaido Tokai University during the winter of 1983-1984.

2. CONSTRUCTION TEST

2.1. Construction Method.

The ice shell should have the facility to be constructed rapidly, easily and economically to provide expedient structures during winter. By taking hints from the erection method of existing reinforced concrete shell (Joedicke ; 1962),the author proposed a rapid, easy and economical construction technique of the ice shell, and had already applied this method successfully to some models with 5-m span.

Enlarging the scale of the model further, the author tried to construct an ice dome with 10-m span by the following method.

1. Polypropyelen guy ropes are anchored to steel bars staked to the ground peripherally. The ropes

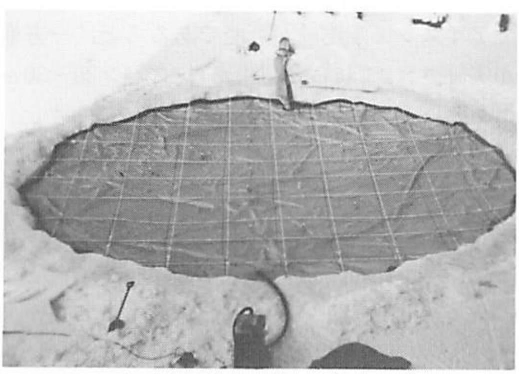

Fig. 1 Placing membrane on the ground

Fig. 2 Air-inflated membrane as formwork

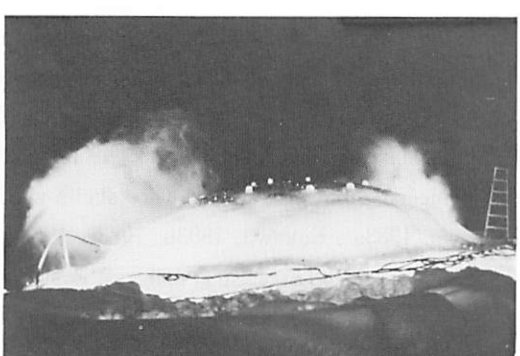

Fig. 3 Application of snow and water

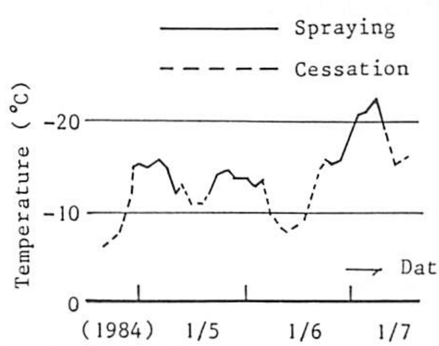

Fig. 4 Outside air temperature under snow and water spraying

are 9 mm diameter, and the diameter, length and total numbers of the steel bar are 25 mm, 80cm and 64 respectively. Subsequently, the peripheral foundation is made by snow and water. At this stage, steel bars are interbedded with the snow-ice foundation ring.

2. A synthetic fiber membrance bag is placed on the ground as shown in Fig. 1. This membrane is fabricated by welder manufacturing along the periphery after wrapping in two pieces of plane sheets with 10 m diameter.

This bag is easy to fabricate because there is no three dimensional cutting as in a sail or parachute.

3. Each middle rope is laid orthogonally on the membrane and connected with the guy rope by a karabiner. Rope spacing in each direction is 1 m. Ropes play an important part in not only forming the shape of the air-inflated membrane, but also giving the local curvature produced by cutting into the bag. The local curvature, or humped surface, seems to increase structural capacity, including resistace to creep buckling collapse of the ice shell.

4. About 25 pieces of styrene polypropylene (s.p.) boards (90cm × 180cm, 1.5cm thickness) are placed at the narrow annular space between the periphery of the membrane and the foundation.

5. After inflating the membrane bag in a short time by a sirocco fan (max. air pressure 5 cm water head, max. air. flow 20 m^3/min.), inner pressure of the inflated membrane in held at 6 cm water head by a voltex blower and a pressure controlling machine. Fig. 2. shows the air-inflated membrane as a formwork.

6. The space between the periphery of the membrane and the foundation ring is filled up by snow and water, then frozen.

7. As shown in Fig. 3, snow is blown onto the membrane by two rotary snowplow with maximum throwing distances of 6 m and 13 m respectively, and tap water is sprayed on the snow by the adjustable nozzle. As a result of this operation, a snow-ice sherbet is produced on the membrane, and it is frozen hard some time later. Freezing and hardening speed of the snow-ice sherbet is primarily depend upon the outside air temperature. It is desirable for the outside temperature to be below −10℃, because if the temperature is above −10℃, the snow-ice sherbet melts rather than freezes when water is sprayed sequentrally on the solid snow-ice. Fig. 4. shows the outside temperature during construction.

Fig. 5 Removing mewbroue from inside

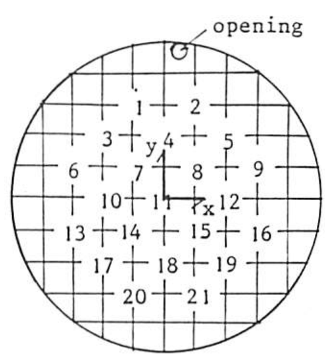

Fig. 6 Inside intersecting point Nos

The application of snow and water are repeated up to the design thickness.

8. After the snow-ice freezes and hardens, the membrane bag is deflated, as shown in Fig. 5, and then the s. p. boards. rope and membarane are removed. The ice shell is then completed.

9. S. p. boards, ropes and membrane bag can be reused. Repeating the above mentioned operations from 1 to 8, additional structures can be constructed.

2.2. Consideration on the Shape.

The ice dome had a small circular opening with about 70cm diameter. Three dimensional coordinate at the inside intersecting points and the shell thickness at the major points were measured after the test dome had been finished.

Fig. 6. and Table 1 show three dimensional coordinates at the inside points of the test dome. Judging from the measurement, these points were nearly on a spherical surface, its radius computed by means of least squares was 7.65 m

In this article, a computational method to predict approximately the coordinate of the intersecting points is developed, and then the computed value is compared with the observed value for the central height of the test dome. In order to simplify the analysis, the following two assumptions are introduced.

1. Friction between the membrane and the rope is free.

2. Load carried from the membrane to the ropes is uniformly distributed normal pressure. As the result of assumption 2, the configuration of the rope after deformation becomes a circular arch as indicated in Fig. 7. Considering that the initial ropes are straight lines, the tension strain of a rope e is given by Eq.(1).

$$e = \theta / (2 \sin(\theta / 2)) - 1 \quad (1)$$

Where θ is the open angle after deformation. It is assumed that the constitutive law of the rope in tension is given by Eq.(2).

$$N = ae^{b} \quad (2)$$

N is the rope tension force and a, b are material constants determined from the uniaxial test. Since the area enclosed by the ropes is 1 m× 1 m in this construction, N can be written as follows.

$$N = 5\,HL_o / (2 \sin(\theta / 2)) \quad (3)$$

Where H,L_o are air pressure and initial rope length respectively. Units of N, H, L_o are kg, cm water head, m respectively. From Eq. (1), (2) and (3), Eq. (4) is obtained as follows.

$$5\,HL_o / (2 \sin(\theta / 2)) = a(\theta / (2 \sin(\theta / 2)) - 1)^{b} \quad (4)$$

Eq.(4) shows that θ is the function of H. In this case, the values of H, L_o,a, b are 6 cm water head, 10 m, 2126kg, 1.188 respectively. Substituting these values for Eq.(4), becomes 98.8 degrees. Consequently, the computed height of the central point, 2.3 m, is in fair agreement with the observed value, 2.2 m.

The distribution of the observed thickness didn't become uniform because of unskilled snow blowing during construction, as shown in Fig. 8. The central part was thinner than the other parts.

2.3. Aesthetic Considerations.

Adter the trial construction, an aethetic presentation was carried out in the night using coloured lights, inside the dome. Both the interior and the exterior were fantastic and beautiful. The interior had a brileiant space and its square grid pattern accented the curved surface.The exterior looked like a gigantic chandelier as shown in Fig. 9.

2.4 Some Problems.

This construction method seems rapid, easy and economical. However, the following future problems have to be solved.

1. Temperature crack : When the first water was sprayed again on the cold snow-ice after breaking

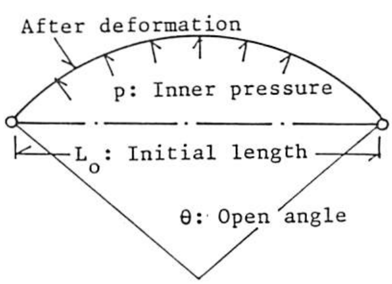

Fig. 7 Analytical model of a rope

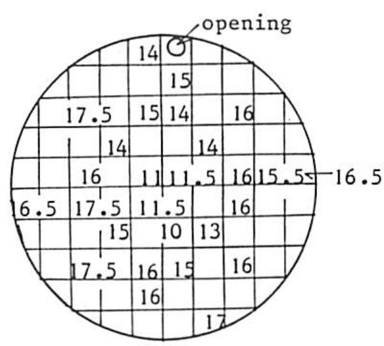

Fig. 8 Observed thickness of snow-ice at major points (cm)

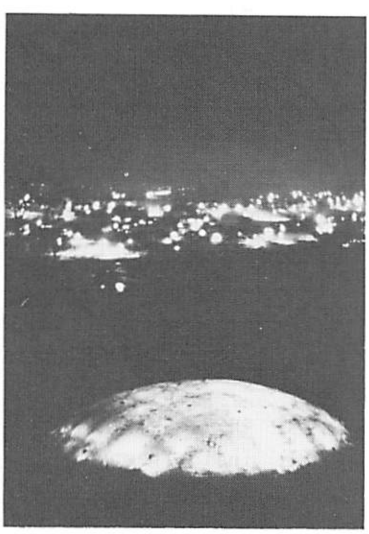

Fig. 9 Exterior view like a gigantic chandelier

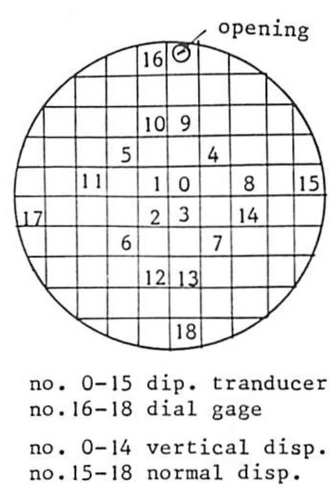

Fig. 10 Point Nos. for measuring displacement

off for half a day, temperature cracks formed. This seemed to be caused by the difference in temperature between the water and snow-ice. Since these cracks are not propagated widely through the structure, it neither gives rise to the general failure during construction, nor affects ceep stability, since the dome is a compressive structure. However, if the strucure experiences tension and bending, this deficiency could affect the mechanical capacity of the structure.

2. Rope Anchor : Considering the mechanical behaviour and the execution of the snow-ice foundation, the present method which anchors the guy rope to the steel bar staked in to the ground is not rational. It seems that, instead of the steel bar, log timbers along the periphery are better for rope anchoring.

3. Filling up the space between membrane and foundation : Because of cutting into the s. p. boards by the ropes, some piecies of s. p. boards were impossible to reuse.

3. CREEP TEST

3.1. method of Mesurement.

As shown in Fig. 10, nineteen points for measuring displacements were prepared at the inside surface of the test dome. The displacement transducers were used for points Nos. 0 — 15, and the dial gages were used for the remaining points. Where the displacements of point Nos. 0 — 14 indicate vertical displacement and that of point Nos. 15—18 indicate normal displacement. The hanging method was adopted so as to measure easily the vertical displacements at the central parts of the dome. This method seems to be available more and more when the tested structure is getting large. The configuration of the hanging method is shown in Fig. 11.

Fig.12 shows ten points for measuring temperature. Two are outside, three inside, and five snow-ice

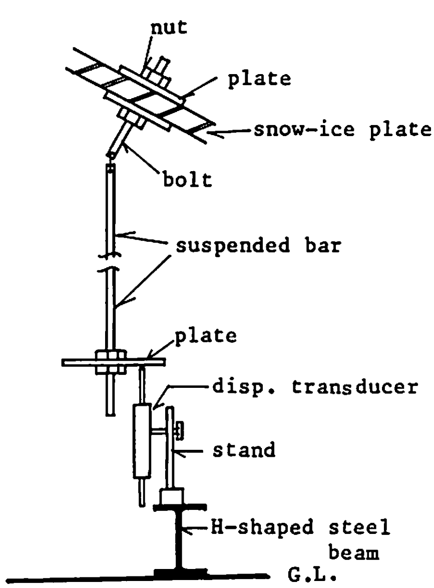

Fig. 11 Configuration of Hanging method

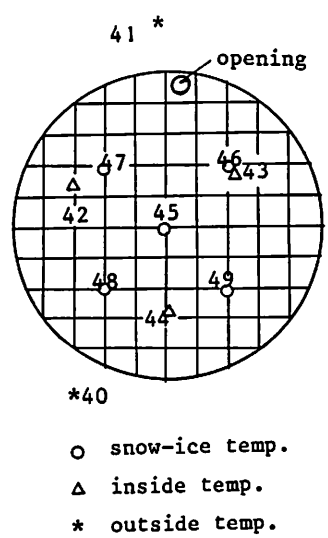

Fig. 12 Point Nos for measuring temperature

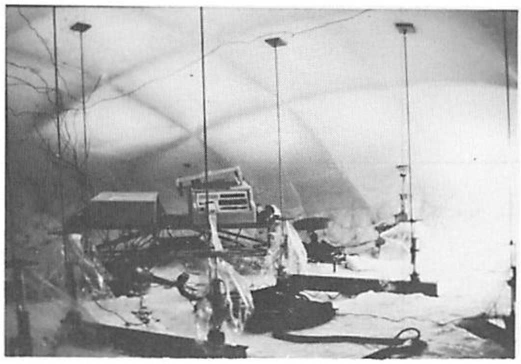

Fig. 13 Inside view under measurement

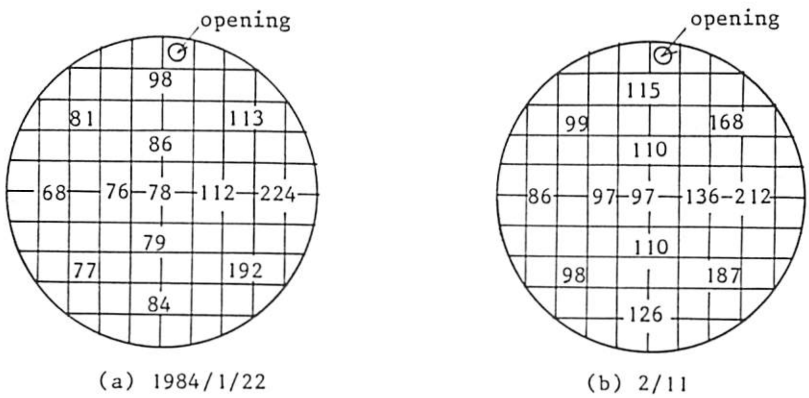

Fig. 14 Observed snow load (kg/m²)

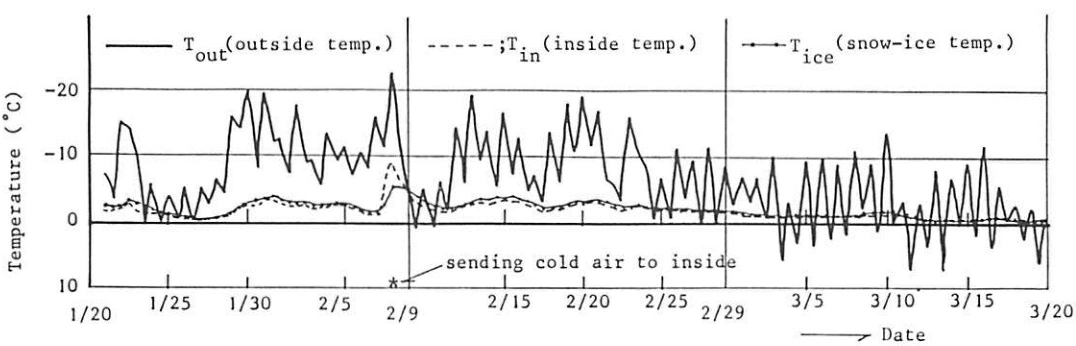

Fig. 15 Temperature-time curves

temperatures were measured by copper-constantan thermocouples. Displacements from point Nos. 0 to 15 and all temperatures were recorded automatically by a programmable date logger at adequate intervals (2, 3 hours) from the beginning to March 20. Fig. 13 shows the inside of the dome under measurement.

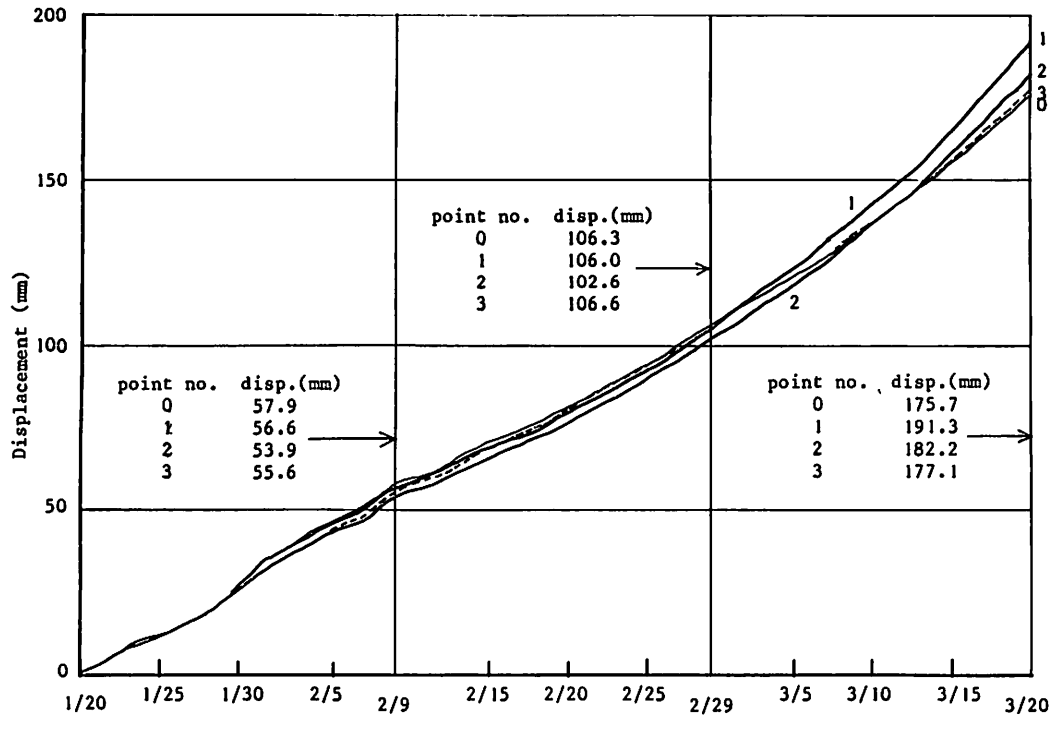

Fig. 16(a) (δ_0-δ_3)-time curves

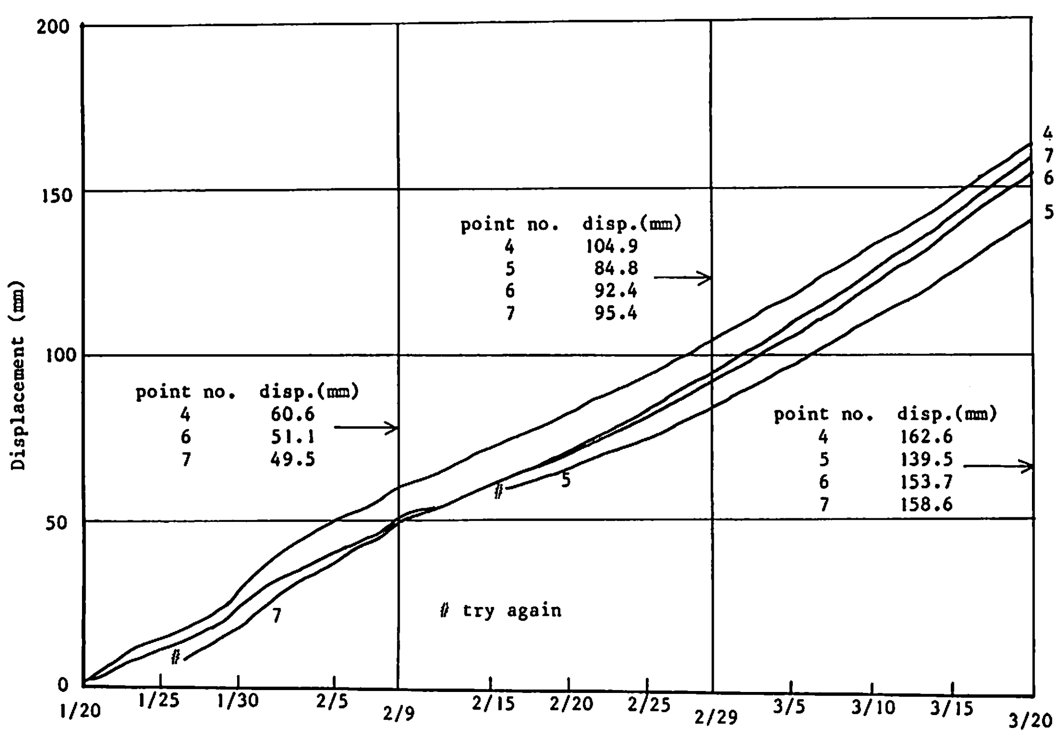

Fig. 16(b) (δ_4-δ_7)-time curves

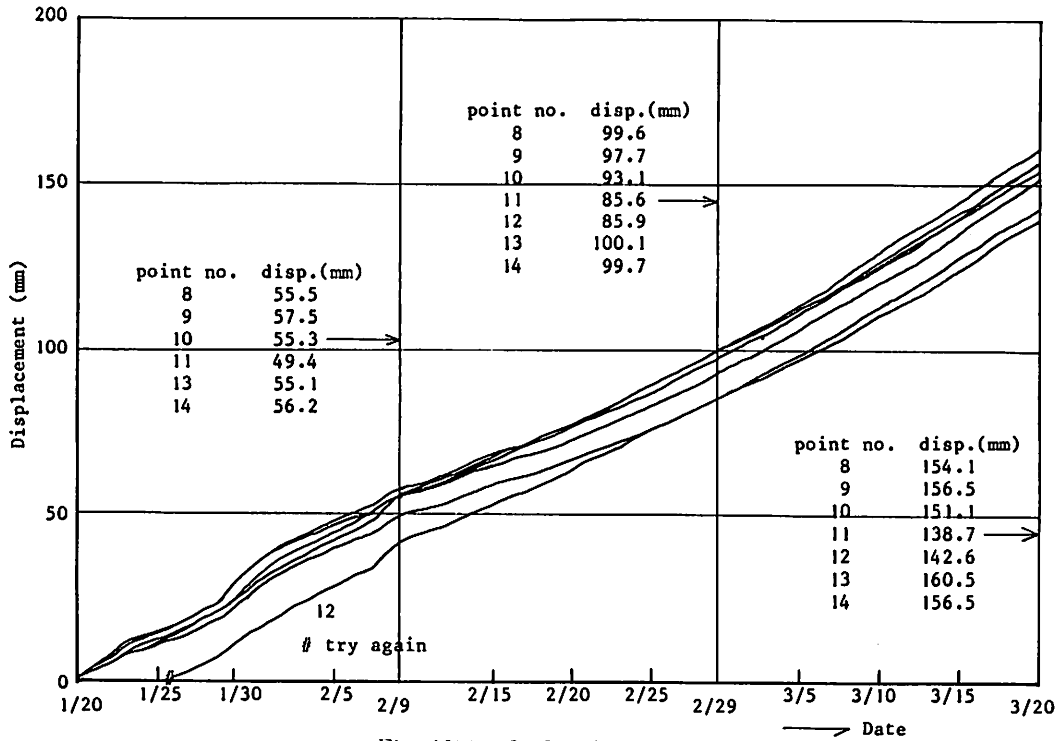

Fig. 16(c) (δ_8-δ_{14})-time curves

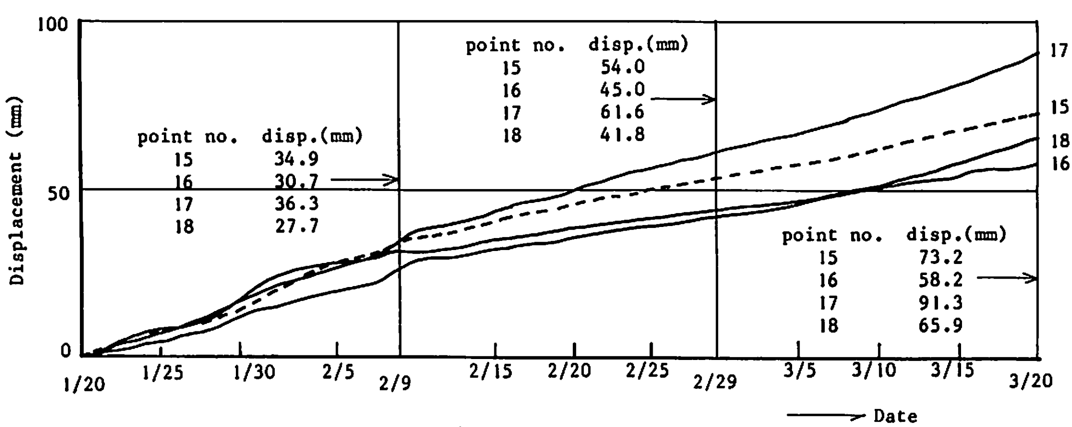

Fig. 16(d) (δ_{15}-δ_{18})-time curves

3.2. Method of Loading

Snow Load was applied to the test dome. The snow was blown onto the dome by the snowplow at the beginning stage. Fig. 14(a) shows snow loads at several points measured by a thin wall sampler at that time.After that, snow load increases somewhat because of snow-fall as shown in Fig. 14(b). Fig. 14 shows the load distribution is not uniform because of unskilled blowing and the wind effect. According to Asahikawa Observatory's meteorological data, precipitation from January 20 to March 20 was 69.5 mm, and this value corresponds to a load of 69.5kg/m^2. Therefore, in this test the snow-fall load is lower than the blowing snow load during the measurement.

3.3. Results and Discussions

Fig. 15 shows three temperature-time curves. Where Tout, Tin and Tice are outside, inside and snow-ice temperature at representative points 40, 44, 45 respectively. Tin and Tice are higher and change more slowly than Tout, due to the thermal insulation effect of snow and snow-ice, as in the previous field study on the 5-m span ice dome (Kokawa, 1985). Rise in Tice is not desirable as regards the creep behaviour. On the other hand, high Tin gives a more comfortable environment. When Tice and Tin are too high in this test. It seem easy to decrease Tice and Tin by enlarging the opening opening with a stiffened edge beam. Although Tout often rose to more than 0 ℃ since the be beginning of March, Tin and Tice were still below 0 ℃ and the dome did not collapse immediately. In fact, it was April 7 when the dome collapsed.

Fig. 16 shows displacement-time curves from the beginning to March 20. Points Nos. 5, 7, 12 caused trouble in the course of measurement, and the displacement transducers were set again. Therefore, only the displacements at the Nos. 5, 7, 12 don't indicate displacement from the start. Taking a broad view of Fig. 16, the deformation grows linearly with time from the start January 20 to the end of February, and then accelerates. Observed displacements of the point Nos. 15 to 18, on peripheral parts of the test dome, were one-third of displacements at the central parts during the steady creep stage. When the boundary is pinned or clamped, the peripheral displacements are about 1/10 of the central displacement due to the linear analysis shown in preceding paper (Kokawa and Hirasawa, 1983a). Therefore, the author analyzed the test dome considering the sectional area of the edge beam. The linear analysis was investigated based upon the following mathematical model. The average thickness is 12.5cm, and the density of the snow-ice material is 0.85 g/cm³. The radius of the dome is 7.65 m as prescribed at section 2.2, and open angle is 98.8 degrees. The sectional area of edge beam is 0.4 m² (50cm × 80cm). The snow load is considered to be a dead load and its unit weight is 110kg/m².As a result of this analysis, there exsisted the following relation between the creep coefficient and the incremental displacement at the center, $\Delta\delta c$ (mm) in a day.

$$\eta = 9.77 \times 10^{-10} \cdot \Delta\delta c \quad (\mathrm{strain}/((\mathrm{kg/cm^2})\,\mathrm{sec})) \qquad (5)$$

If $\Delta\delta c$ takes 2.2 mm/day, η becomes $2.16 \cdot 10^{-9}$. The value of η is lower than the previous value (Kokawa, 1987) for the 5-m ice dome, perhaps because of the humped surface effect. A humped shell improves the structural capacity by increasing the equivalent of inertia as compared with usual monocoque shell. The qualitative estimation of humped effect is a very important problem to be solved in the future.

As shown in Fig. 15, cold air was sent to the inside of the dome by the sirocco fan on February 8 in order to check the thermal effect. As a result of this experiment, it was shown that the rate of the observed displacement is large when Tice falls for a short time, and small when it rises. If Tice changes sharply, the thermal deformation is larger than the creep deformation.

The central deformation accelerates gradually with time from the beginning of March. The rate of

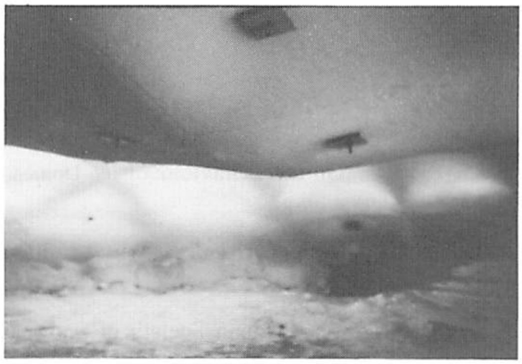

Fig. 17 Deformation at onset of collapse

displacement at point no.1 is 5.3 mm/day at the end of measurement. It appears that this is due to the increase of η by rising Tice, the increase in load by snow fall and the geometrical nonlinearity. On the other side, the rate of the peripheral displacement did not vary with the time.

After the measurement, on March 20, the structural behaviour was observed by eye up to the collapse. The deformation near point Nos. 1, 2, increases suddenly, and the occurence of the anti-symmetrical mode was observed at the about a week before the collapse. It should be noticed that the location of the hollow undertake small snow load comparatively. At the onset of the collapse, the deformation was about 100cm which means 8 times the shell thickness, as shown in Fig. 17. It indicates that the snow-ice structure is more ductile than expected. In other words, the collapse does not occur abruptly, and we have enough time to predict the danger of collapse.

4. CONCLUSION

A field study on both the construction technique and the creep test of the ice dome with 10-m span was performed at Asahikawa during the winter of 1983−1984.

The structure was constructed by the following method. Inflating a membrane air bag covered with rope by sirocco fan and blower, spraying the snow-ice sherbet on it, then removing the bag and ropes for reuse. This method satisfies foundamentally the facility of a rapid, easy and economical construction, though some minor improvements are needed. After completion, inside intersecting points of the domes were measured, and they agreed with values computed by a simplified method. Subsequently, a creep test was carried out under snow load, and structural behaviour up to collapse was examined. It is gathered from the creep test that the ice shell structure is very ductile, and the humped shape will bring an improvement in structural efficiency.

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REFERENCES

1) Jurgen Joedicke (1962) : Schalenbau, pp. 138-139., Karl Kramer Verlag, Stuttgart.

2) Kokawa, T. and Hirasawa, I. (1983a) : On the Behaviour of Ice Domes under Short Term Loading, Bulletin of Hokkaido Tokai Univ., No. 3, 4. . 77-85.

3) Kokawa, T. (1983b) : Experimental Study on Creep Buckling Collapse of 60-cm Span Ice Dome, Japan NCTAM, Vol. 33. . 151-152.

4) Kokawa, T. (1983c) : A Study on Ice Shell, Japan Society of Snow and Ice (Annual Meeting) 108.

5) Hirasawa, I. and Kokawa, T. (1984a) : On the Creep Behaviours of 2-M Span Ice Dome, Bulletin of Hokkaido Tokai Univ., No. 5 7-15.

6) Kokawa, T. (1984b) : Axisymetric Creep Buckling Analysis of Ice Domes, Bulletin of Hokkaido Tokai Univ., No. 5 : 17-24.

7) Kokawa, T. (1984c) : A Field Study on Ice Shell, 25th International Symposium on Shell and Spatial Roof Structure, Dortmund, West Germany.

8) Kokawa, T. (1987) : An Experimental Study on Creep Collapse of Ice Dome, Bulletin of Hokkaido Tokai Univ., No. 7 .

9) Sapporo Meteorological Agency(ed). (1982) : Climate in Hokkaido, Published at Hokkaido Office, Japan Weather Association.