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An Experimental Study on Creep Collapse of Ice Dome*

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アイスドームのクリープ崩壊実験

粉川　牧

1981－1982の冬期間，スパン5mアイスドームのクリープ実験を行った．供試体は立体裁断された一重空気膜（曲率半径3.53m，開角90度の部分球面）構造に雪と水を吹きつけて作られた．試作後の雪氷厚は平均で9.4cm，雪氷比重は約0.85であった．

クリープ実験は，1袋20kgの砂袋により3ton頂点近傍に集中的等分布となる様載荷し，崩壊直前迄の約1ヶ月にわたり，法線方向変位，温度（雪氷，ドーム内，外）を自動測定して行われた．崩壊時間×荷重×クリープ係数で定義される無次元クリープ座屈値を導入し，実験値と古典値(一様外圧を受ける完全球の線形クリープ座屈値)の比率を求めたところ，0.63：1となり，既往のスパン60cm，2mモデルの実験値と良く対応した．

ABSTRACT

A field study on a reduced scale model of a 5-m span ice dome was developed. The model was constructed as follows. The snow-ice sherbet is produced on the air-inflated membrane by spraying snow and water. This operation is continued up to the design thickness. After freezing and solidifying of snow-ice, the membrane is removed. Experimental study on the structural safety against creep collapse was conducted as follows. Axisymmetric distributed load was applied to the test dome on a circular area concentric with the apex. Normal displacements and temperatures were measured up to the collapse. Experimental collapse time was examined, introducing the classical creep buckling value of a complete spherical shell under uniform external pressure.

1. INTRODUCTION

Mechanical properties of ice and snow-ice have been studied in the field of glaciology (Hobbs, 1974). Putting the results of fundamental study on ice physics to engineering practice use, developments and

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researches of ice structures have been carried out in the cold regions. Ice Bridges (Michel et al., 1974) for winter road crossing the rivers and Ice Platforms (Fjeld, 1983) for northern submarine oil field are the case in that point.

An ice shell structure may be also considered to be a suitable example for making practical use of ice and snow-ice as structural material and may be an efficient architectural solution to the certain probems of the cold regions (Stanly and Glockner, 1975 ; IL 9, 1976 ; Isler, 1979).

The ice shell is thin, and its structural material is snow-ice. If the ice shell covered relatively large area, it could be used for a variety of expedient shelters, such as sport-leisure centers, festival halls, ware houses and car sheds etc. during witer in the snowy and cold regions.

Aiming at the production of ice shells spans from 20 to 30m, the author has been making experimental and theoretical investigations on both the structural safety and the construction method of the ice shell by reduced scale models for four years.

Experiments and analysis on ice domes with 60-cm span under short-term loading (Kokawa and Hirasawa, 1983a). experiments on ice domes with 60cm (Kokawa, 1983b). 2 m (Hirasawa and Kokawa, 1984a). 5 m (Kokawa, 1983c). 10 m span under long-term loading, and the axisymmetric creep buckling analysis of ice dome (Kokawa, 1984b). were developed as investigations on the structural safety. At the same time, an ice shell constuction method proposed by the author has been tested for models with spans of 5 m and 10 m (Kokawa, 1984c).

This paper mainly describes a field study on the creep collapse by the reduced model of a 5-m span ice dome performed at the University of Hokkaido Tokai in Asahikawa during the winter of 1981-1982.

2. THEORETICAL BACKGROUND OF THIS STUDY

As is generally known, thin shell structures have usually enough stiffness and load carring capacity in comparison with their own weight, and are used to span wide roofs.

By comparing the mechanical properties of flat plates and shells, it can be understood how shell structures have superior structural efficiency.

Fig. 1 shows configurations of a spherical shell and a flat plate, each with 30cm thickness and 30m dia-

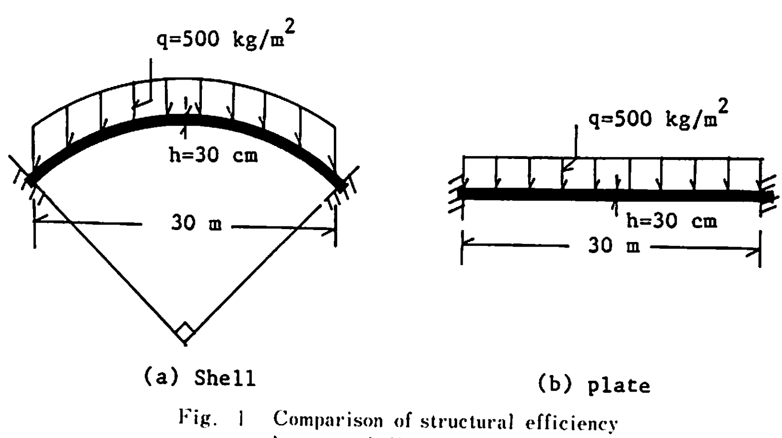

Fig. 1 Comparison of structural efficiency between shell and plate

meter. Comparisons of stress and deflection are made at the central point of these structures. The methods of computation are based upon membrane theory in the case of the shell, and thin plate theory in the case of the flat plate (Timoshenko and Krieger, 1959) . The results are as follows.

1. $\sigma s : \sigma p = 1 : 37$, where σs, σp are the stress of the shell and the plate respectively. With a vertical unit load of 500 kg/m², σs becomes 1.8 kg/cm², in compression. This value is about 1/25 of the uniaxial compression strength of snow-ice (Kokawa and Hirasawa, 1983a).

2. $\delta s : \delta p = 1 : 273$, where δs, δp are respectively the vertical deflections of shell and plate. If Young's modulus E is 5 t/cm², σs becomes 7.5 mm.

conseqently, even if the structural material does not have enough strength and stiffness, like as snow-ice, it is possible to cover a relatively large span by using a shell structure.

3. EXPERIMENTAL STUDY ON CREEP COLLAPSE OF 5-M SPAN ICE DOME

As prescribed in the section 2, the strength of an ice shell may be sufficient for some given loads under short period. However, since the snow-ice creeps, it is important to investigate the creep behaviour of an ice shell which will experience loads for a long time.

According to the experimental study on the creep buckling of 60-cm span models (Kokawa, 1983b) under constant load and temperature, as same as high temperature metal vessels (Gerdeen and Sazawal, 1974), the deformation grows with time through the primary, secondary and tertiary stage of creep, and then the structure collapses. After all, the phenomenon of the creep buckling collapse is governed by a critical time as well as a critical load. Therefore, for appreciable lifetimes and given any load, the creep buckling collapse should be avoided. It is not too much to say that lighting upon this phenomenon holds the key to the application of ice shells.

3.1 Construction of Test Model

The test model has 5 m diameter and 90 degrees open angle, as shown in Fig. 2. Such a model, with simple geometry, facilitates analysis of the experimental results. The model was constructed as follows.

1. The boundary of the synthetic fiber membrane is fixed and sealed by bolts at the side wall of a

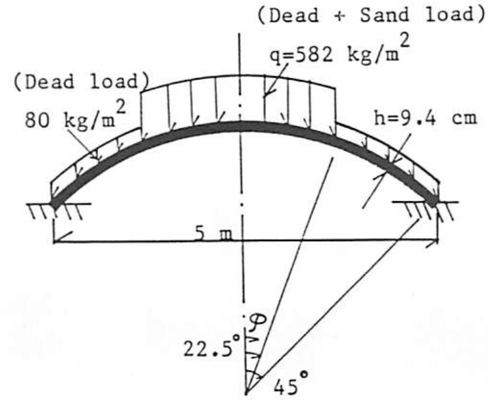

Fig. 2 Analytical model of span 5 m ice dome

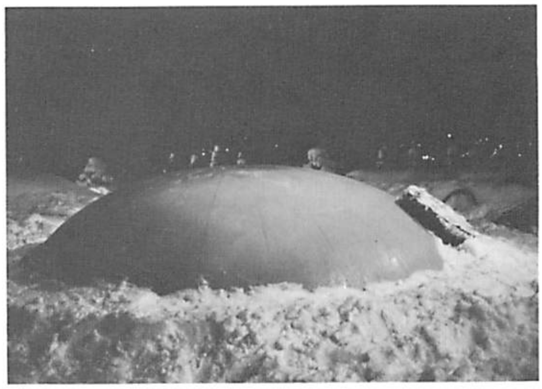

Fig. 3 Air-inflated membrane as tormwork

reinforcement concrete foundation ring with 5 m inside diameter. In fabrication of the membrane which serves as formwork for the erection of the desired spherical dome, 24 spherical triangular segments were cut, and were joined by means of welding along the longitudinal line.

2. The membrane is air-inflated by a voltex blower, and the inner pressure is held at 6 cm water head by a pressure controlling machine, as shown in Fig. 3.

3. Snow is blown on to the membrane by a rotary snowplow, and tap water is sprayed on the snow by the adjustable nozzle, as shown in Fig. 4. As a result of this operation, snow-ice sherbet is produced on the membrane, and it freezes hard some time later. The application of snow and water is repeated up to the desired thickness.

4. After the snow-ice freezes and hardens, the membrane is deflated and removed. The membrane can then be re-used.

3.2 Method of Creep Test

Axisymmetric distributed vertical load was applied to the test dome by placing 20kg sand bags on a

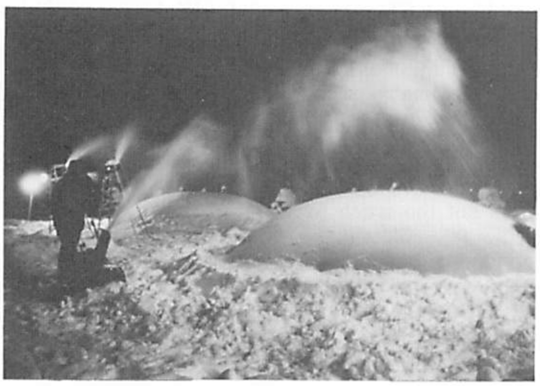

Fig. 4 Blowing snow and spraying water on the membrane

Fig. 5 Loading

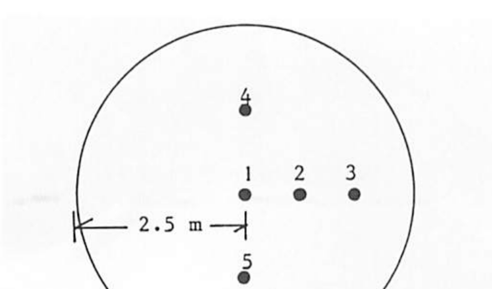

Fig. 6 Mesuaring point Nos. of displacements

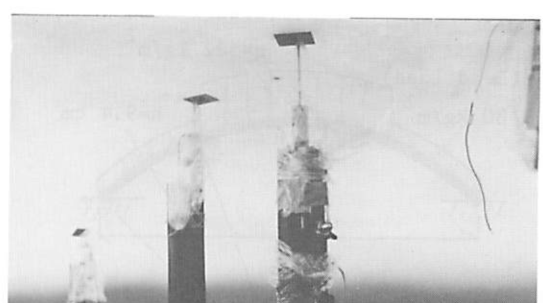

Fig. 7 Installation of displacement. transducer

circular area ($\varphi \leqq 22.5°$) cencentric with the apex, as shown in Fig. 5. The total sand load on the dome was 2 tons from the beginning to January 26 in 1982, and 3 tons from January 26 to the collapse, respectively. Vertical loads shown in Fig. 2 are determined by assuming that the density of the snow-ice is 0.85 g/cm³, the total sand load is 3 tons, and the shell thickness is 9.4cm.

Fig. 6 shows the projective points to the plan for measuring the normlal displacements. Each displacement was measured by a displacement transducer which was set up the top of H-shape steel column, as shown in Fig. 7. Outside, inside and snow-ice temperatures were measured by copper-constantan thermocouple. Displacements and temperatures were recorded automatically by a programmable data logger every 2 to 3 hours.

3.3 Results and Discussions

Fig. 8 shows three temperature-time curves during the whole experiment. Tout, Tin and Tice are outside, inside and snow-ice temperature respectively. The average values of Tout, Tin Tice are −9.65℃, −3.90℃,and −5.53℃ respectively. Under the condition where the dome has a small opening and some snow cover like this, Tin and Tice are about 5 degrees higher on the average temperatures and change more slowly than Tout, due to the thermal insulation effect of the snow cover and the snow-ice. Although rise in Tin and Tice is not desirable as regards the mechanical property of the snow-ice, it gives more a comfortable environment for work and play. Just after removing the snow on the dome, Tin and Tice change sharply, as shown in Fig. 8.

Fig. 9 shows displacement-time curves from the beginning to the collapse. δi is the displacement at i point shown in Fig. 6, and each desplacement excepts the displacement caused by the thermal expansion of the snow-ice. Preceding the loading creep test, each displacement under only the dead load was measured with the variation of Tice. As the result of this experiment, it was shown that the direction of the observed displacement is down when Tice falls. and up when it rises. It was concluded that the displacement was caused by the thermal expansion of the snow-ice. The computed thermal expansion

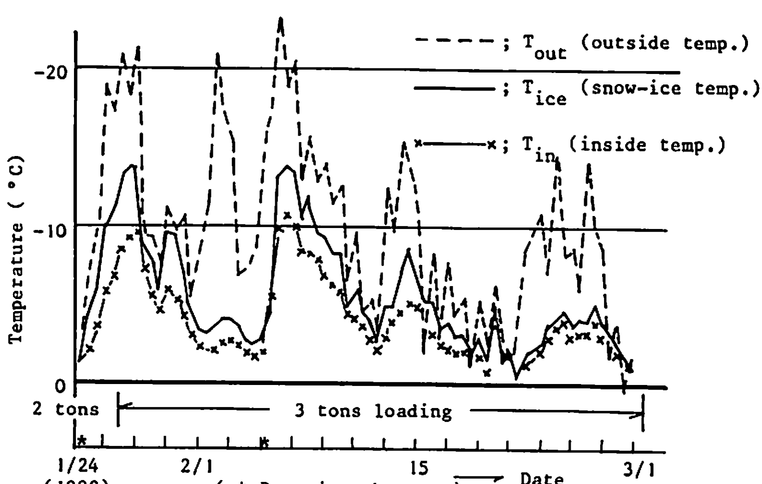

Fig. 8 Temperature-time curves

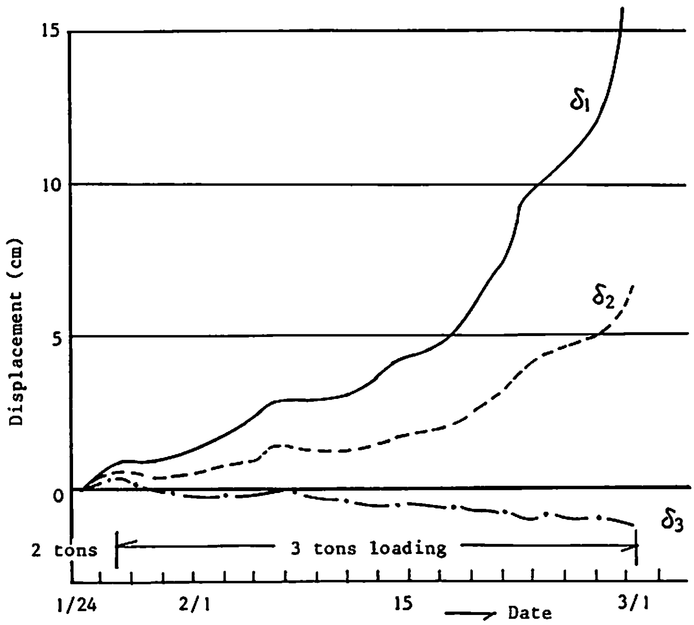

Fig. 9 Displacement-time curves

coefficients of the snow-ice at each point, based upon the observed desplacement and shell membrane theory, is about 50% greater than that of polycrystalline ice as reported in the literature (Tokyo Astronomical Observatory, 1982). The behaviour of each displacement during two days just after the beginning and from February 5 to February 9 is beyond the author's understanding, though frost heaving or thermal effect may be considered as its cause.

Taking a broad view, the central desplacement-time curve is qualitatively similar to the behaviour under constant load and temperature That is, the deformation grows linearly with time during from the beginning to February 17, when the displacement reaches half of the shell thickness and thereafter accelerates up to creep collapse.

Assuming that the constitutive law of the snow-ice obeyed in accordance with linear Newtonian flow (Eq. (1)), and there is no vloume change under creep, and linear shell theory is valid. The normal deformation and the stresses in this model (Fig. 2) were computed by means of the previous method (Kokawa and Hirasawa, 1983a)

$$e = \eta \sigma \qquad (1)$$

Since the theoretical stresses are low as shown in Fig. 10, it seems appropriate to use Eq. (1), where e, η and σ are strain rate, creep coefficient and stress respectively under uniaxial compression or tension.

Fig. 11 represents the η -Tice relation during from February 1 to Febuary 17 when the observed each displacement seem to be not affected so much by frost heaving and geometrical nonlinearity. η is evaluated as follows.

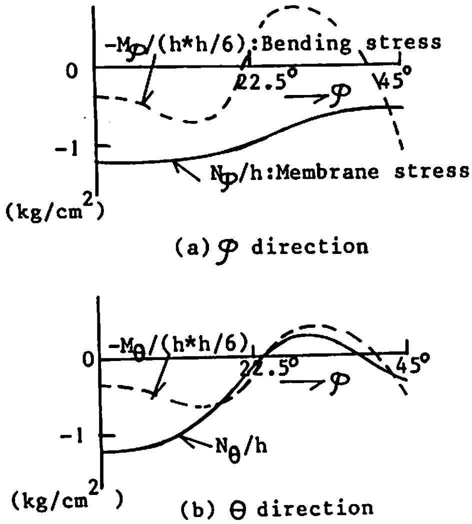

Fig. 10 Theoretical stress distributions

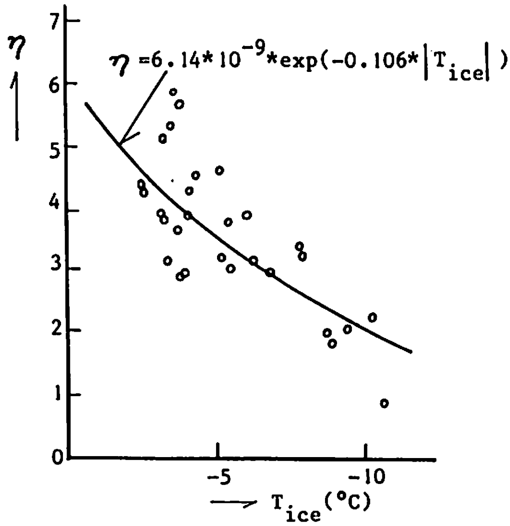

Fig. 11 η(*10⁻⁹*strain/((kg/cm²)*sec))-Tice

First, the function f is defined as Eq. (2).

$$f = \sum_{i=1}^{3} (cy_i - (\Delta \delta i + d))^2 \qquad (2)$$

Where i is from 1 to 3, y_i, $\Delta \delta i$ are the theoretical displacement velocity (cm/s) for η = 1 strain / ((kg /cm²) sec) , the observed incremental deslpacement (cm) for half a day, respectively at i point. In this analysis. y_1, y_2 and y_3 are taken as 728, 541, −51.7 respectively. Then c was determined so as to minimize the function f with respect to c and d. Finally, η is computed by Eq. (3).

$$\eta = c/(60 \times 60 \times 12) \ (\text{strain} /((\text{kg/cm}^2) \ \text{sec}) \qquad (3)$$

As shown in Fig. 11, η is directly related to T ice, which is the average for half a day. The present data can be represented by the empirical relation Eq. (4).

$$\eta = A \exp\ (-B |T\ ice|) \qquad (4)$$

The values of A and B were determined by a least squares fit as $6.14 \cdot 10^{-9}$ and 0.106 respectively. The value of η was somewhat higher than the values given by the exisiting creep test (Mellor and Smith, 1966).

Now, in order to evaluate the experimental collapse time and load, let us introduce the dimensionless experimental creep buckling value α cr, defined by Eq. (5).

$$\alpha\, cr = (\eta\, t\, q)cr = \eta\, av\ tcr\ q \qquad (5)$$

Where η av is given by substituting the average T ice during the whole experiment (−5.53℃) in Eq. (4). tcr and q are the collapse time and the unit load respectively. In this case, each value is taken as follows.

$\eta_{av} = 3.42 \cdot 10^{-9}$ (strain/ ((kg/cm²) sec)

tcr = 34.5(days), q = 582(kg/m²)

Then from Eq.(5), $\alpha_{cr} = 5.93 \cdot 10^{-9}$. Subsequently, a dimensionless creep buckling value α_{cro} is introduced as a standard value. α_{cro} is obtained by transforming the classical buckling formula of a complete spherical shell under uniform pressure (Timoshenko and Gere, 1961). α_{cro} is expressed by Eq. (6).

$$\alpha_{cro} = 4/(3\lambda^2) \tag{6}$$

λ is radius / thickness, 37.7, so that $\alpha_{cro} = 9.38 \cdot 10^{-4}$. Finally, $\alpha_{cr} / \alpha_{cro}$ is 0.63.

This value is in the range of the previous test results (Kokawa, 1983b). According to the author's analysis with respect to axisymmetric creep buckling of ice domes (Kokawa, 1984b), it is shown that the $\alpha_{cr} / \alpha_{cro}$ at uniform loading is larger than that at the concentratedly distributed load. However, even taking into account the above, the ice shell with 30-m span is in danger of creep buckling collapse in a short period i. e., one or two months. Consequently, a procedure for increasing the effective shell thickness by humped effect will be described in a following paper (Kokawa, 1987). This should be done so as to prolong the occurrence of creep buckling collapse.

4. CONCLUSION

The experimental study on 5-m span ice dome was carried out at Asahikawa during the winter of 1981-1982. To construct easily, rapidly and economically, the test model was made as follows.

Snow and water were sprayed on the air inflated membrane up to the design thickness. After freezing and solidifying, the membrane was removed. Subsequently, a creep coefficients inferred from the observed displacements and linear shell theory, the collapse time, load, and dimensionless experimental creep buckling value α_{cr} were computed. At the result, α_{cr} was 63% of the dimensionless classical buckling value as a standard value and it found that evaluation of the creep buckling collapse is one of the most important investigatiolns in the design of ice shell structures.

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