ICE SHELL CONSTRUCTION FOR WINTER ACTIVITY

Tsutomu Kokawa
School of Design, Hokkaido Tokai University, Asahikawa, Japan
kokawa@da.htokai.ac.jp

Abstract

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. It is a new type of ice structure based on modern structural engineering and it can cover a larger than the classic snow-ice structures such as the Japanese ”*kamakura*” or the igloo.

This paper consisting of 1) the construction method etc., 2) the recent application to winter architecture in Hokkaido, 3) a field experiment of Ice Domes spanning 20-30 meters and 4) a theoretical investigation of Ice Dome on frozen lake-ice plate, suggests that the ice shell, as a concept in architectural technique in cold and snowy regions during winter, could be utilized for winter activity.

Introduction

Snow and ice have been long used as a structural material for constructing temporary enclosures in cold and snowy regions. Floating ice-platform to support offshore drilling operations on the arctic sea (Baudais et al., 1974), ice bridges for heavy transportation (Michel et al., 1974) and ice-cover on a river for the railway track during the World War II (Kubo, 1980) are well known ice structures as the examples of civil engineering structures.

On the other hand, an ice shell, which would provide an efficient solution to certain problems common in cold and snowy regions, is considered to be a kind of architectural ice structures. The shell is thin, and its structural material is ice. It is a new type of ice structure based on modern structural engineering and it can cover a 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 for creating a unique built environment (Kokawa, 1985).

Structural Engineering of Ice Shell Construction

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 Japanese traditional snow hut where children play house during the New Year holidays, and 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 the following simple, quick and economical method (Kokawa, 1985):

(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 (1cm) by blowing the milled snow with a rotary snow blower and 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 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.

Feature of Pneumatic Form

One of the most featuring things in this construction method, is concerned with the form finding method by the air-inflated formwork. The formwork consists of the membrane and covering ropes. The ropes play an important role in forming the shape of the air-inflated membrane. The tension in the ropes is equilibrium to the force in the air-inflation. The membrane does not need the 3-dimensional cutting, owing to the force control by the covering ropes. So, the membrane is easy to fabricate, even though the 3-dimensional form is complicated. It is supposed many different forms come from the same membrane by changing the length and geometric pattern of ropes. Because these forms are decided automatically under the uniform pressure, the completed ice shell works mainly in compression membrane force, in spite of free-shape shell. So, this structure makes the best use of the ice material, which is strong enough for compression force. Furthermore, its general form chosen automatically by this method is regularly consisted of same convex patterns. A family of reinforced ribs with large sectional areas along the ropes, bring not only the improvement of structural efficiency but also the geometrical beauty at the inside surface.

Snow Blowing and Water Spraying

In order to produce quickly a high quality of ice on the membrane, some special devices are needed. Snow is blown onto the membrane by a snow blower and tap water sprayed on the snow by a high pressure adjustable nozzle. The snow is called "milled snow" which has a strong bond like a ceramic. A snow-ice sherbet produced on the membrane, is frozen hard some time later under the air temperature -10^{o}C below. It is necessary during one blowing operation to keep the milled snow depth to be less than about 1 cm thickness. Otherwise, when water is sprayed, only the snow surface solidify and the membrane cannot hold the form because of excessive weight which cause material and geometrical imperfections as previously reported (Kokawa and Murakami, 1986). The snow-ice sherbet solidifies more quickly than only water because of the low latent heat, and the ice seems to be more ductile. It normally takes 1.5 hour to attain 1 cm thickness. When the ice thickness reaches a certain value, the ice itself can support the weight of a new snow-ice sherbet layer instead of the inflated membrane. Therefore, the membrane does not need a high pressure and the formwork including the foundation is light and low cost. The application of snow and water are repeated up to the desired shell thickness, which is normally about 1/100th of the span.

Creep Behavior

The strength of an ice shell is sufficient for some given loads over a short period. However, as the ice creeps, it is important to investigate the creep behavior of an ice shell which will experience loads for a long time. So, experiments on ice domes under long-term loading (Kokawa, 1983; Hirasawa and Kokawa, 1984a; Kokawa, 1985) and the axisymmetric creep buckling analysis of ice domes (Kokawa, 1984b), were conducted together with at the beginning stage of investigations on the structural safety. Experimental creep tests (Kokawa, 1985; Kokawa and Murakami, 1986; Kokawa, 1988), which were constructed based on the prescribed method, were carried out carefully. The important result of these tests confirmed that the ice shells slowly produce a large creep deformation before the collapse, if the quality of the ice remains good. It indicates also that the collapse does not occur abruptly, and that is enough time to predict the danger of the collapse. This ductile behavior makes use of ice shells possible for architectural structures.

Application to Winter Structure

Based on the fundamental studies since 1980 (Kokawa, 1982/1983), and because of both the easy construction technique and high durability, the following structures have been constructed with an eye toward the experimental use; 10-m span small ice domes have been practically used for a variety of temporary shelters such as a winter storage of vegetables, a factory house for making Japanese "sake", an exhibition hall for a winter festival and a working space at the basement-area for Japan Observatory in the South Pole. The results of these experiences provided the opportunity never

Fig. 1 Ice Shells in Tomamu (2002-2003 winter)

Fig. 2 Tomamu (1998-1999 winter)

Fig. 3 Tomamu (2000-2001 winter)

Fig. 4 Free-shape ice shell (Tomamu)

Fig. 5 Inside of 15-m dome (Tomamu)

Fig. 6 Japanese 'sake' making (Asahikawa)

Fig. 7 30-m long ice tube (Asahikawa)

experienced before to construct ice shells for an architectural space in Tomamu, Hokkaido since 1997. Many ice shells limited to no more than 15m span, have been used as leisure-recreational spaces for visitor about 3 months in each winter and these have created a fantastic, beautiful space (Kokawa et al., 2000).

Field Experiment of Ice Domes Spanning 20-30 Meters

Elastic Consideration

Theoretically, the use of an ice dome with a span of 20 to 30m is feasible. According to the membrane shell theory (Timoshenko and Krieger, 1959), the compression stress at the apex of a spherical shell (with 30m base diameter and 130 degree open angle) under dead type of loading (ice density 0.85 g/cm^3) is computed as 0.71 kg/cm^2, which corresponds to about 1/60th of the uniaxial compressive strength of ice. Therefore, the 30m-span ice dome has enough strength to stand, theoretically. This is the reasoning behind the field experiment of the 20~30m-span ice dome concerning the construction technique and the structural safety, which was subsequently conducted.

Field Test of 20m-Span Ice Dome

Two field studies on a 20m-span ice dome (17m base diameter and 6.5m height) were carried out at the site of Tomamu in 1999 and 2000. The following Figures and Pictures describe the construction and creep test of the year 2000's test-dome, and concludes that a 20m-span ice dome, as an architectural structure during winter in Hokkaido, is feasible.

Fig. 8 Air-inflated membrane as formwork

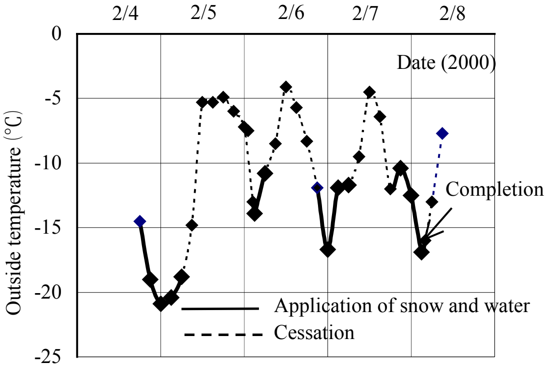

Fig.9 Outside air-temp. during construction

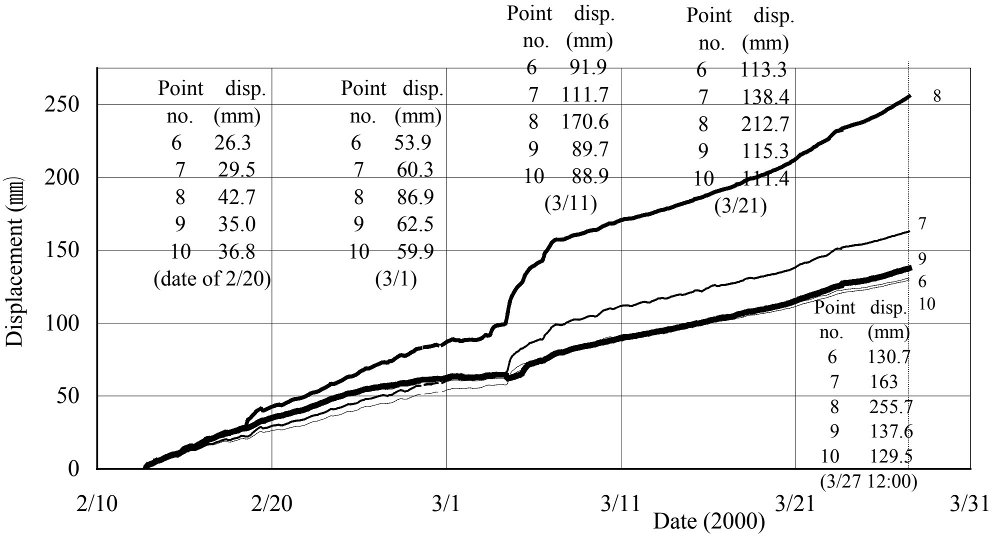

Fig.10 Displacement-time curves

Table 1a Average temperature (^{o}C)

Period Point no.	2/14~ 2/29	3/11~ 3/26	3/4~ 3/7	(2/14~3/26)
Outside	-10.9	-6.5	-2.6	-8.0
Inside	-4.7	-2.5	-1.0	-3.4
Ice (34)	-4.5	-1.6	-0.3	-3.0

Table 1b Average creep displacement (mm/day)

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

Fig.11 Large deformation
right before collapse

Field Experiment of 30m-Span Ice Dome

Following the experiments with 20m-span ice domes, a field study involving the construction and creep test of a 30m-span ice dome (25m base diameter, 9.2m height and 25cm average ice thickness) was carried out at the same site of Tomamu during the winter of 2001. It took six days to complete the construction including the snow-ice foundation work. Following the construction, a creep test was performed and the structural behavior was examined. It was found that the average displacement rate in the central parts of the dome from February 17 to March 23, was about 6.5mm/day, and it was shown that the dome had a sufficient structural efficiency.

Fig. 12 Inflated membrane

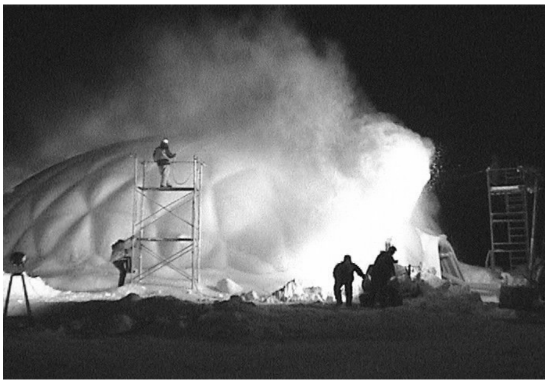

Fig. 13 Application snow and water

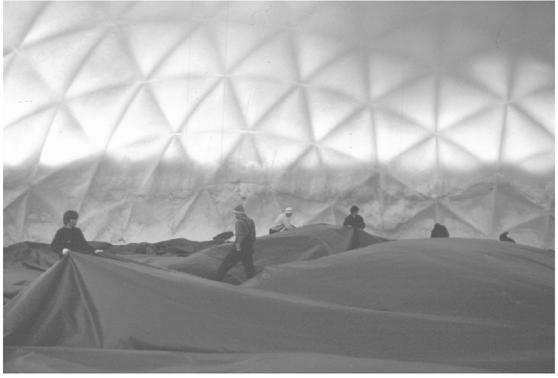

Fig. 14 Removing membrane

Fig. 15 Completion

Theoretical Preparation for Future Application on Lake-Ice Plate

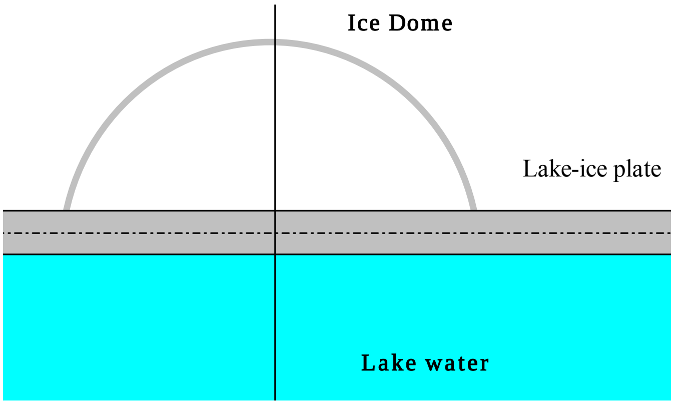

Fig. 16 Ice Dome on lake-ice plate

The Ice Shell could be constructed easily at a place where coldness, snow and water can be prepared, even if there are no heavy equipments for construction. It means the ice shell could be utilized at any place as an expedient structure fitting to various winter activities. Nowadays in Hokkaido, a frozen lake ice plate has been used as a recreational or a festival area such for snow mobile, fishing, skating and so on. Fortunately, there is much water for the ice shell construction beneath the ice plate and it may be easy to construct the ice shell as instant shelters for winter activities. In this situation, the lake ice plate has to support a steady ring load transmitted from a vertical load including the weight of ice dome itself. Assuming that ice is incompressible under hydrostatic stress and that it obeys Maxwell's fluid model for deviatoric stress and strain, a viscoelastic analysis was conducted based on 'thin plate theory' and 'correspondence principle', in order to predict theoretically the creep behavior of the ice plate. As a result of a numerical simulation in the case of 20m span ice dome, it is shown a big buoyant force takes place and reduces a bending stress over the plate, and a 100 cm thickness ice plate will be able to support 100t ring load in total for 2 -3 months.

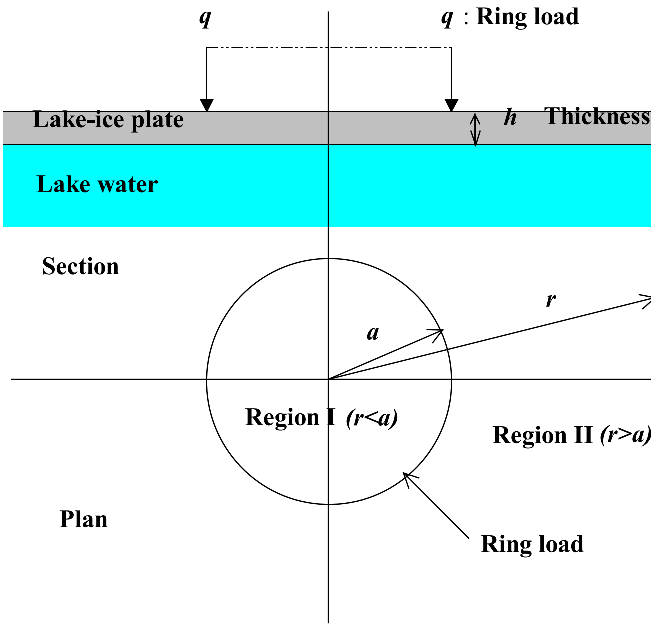

Fig.17 Ring load on lake-ice plate

Elastic Solution under Ring Load

For an elastic plate as shown in Fig. 17, the differential equation is

$$\left(\frac{d^2}{dr^2}+\frac{1}{r}\frac{d}{dr}\right)\left(\frac{d^2w}{dr^2}+\frac{1}{r}\frac{dw}{dr}\right)=\frac{q\delta(r-a)-kw}{D} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Where w is the deflection of the plate, $D\left(=Eh^3/12(1-\nu^2)\right)$ is the flexural rigidity of the plate, E is Young's modulus, h is the thickness of the plate, ν is Poisson's ratio, k is the weight per unit volume of water δ is Delta function and q is the constant load per unit length over the circle of radius a. A solution for the *infinite plate* of Equation (1) is in the following Table 2 (Wyman, 1950).

Table 2 Elastic Solution

	Region I: $r<a$ $(\xi<\xi_a)$	Region II: $r>a$ $(\xi>\xi_a)$
w	$-\frac{l^2}{2\pi D}P_t(kei\xi_a ber\xi+\ker\xi_a bei\xi)$	$-\frac{l^2}{2\pi D}P_t(bei\xi_a \ker\xi+ber\xi_a kei\xi)$
Mr	$\frac{P_t}{2\pi}\left[\begin{matrix}\{-kei\xi_a bei\xi+\ker\xi_a ber\xi\}\\ -\frac{(1-\nu)}{\xi}\{kei\xi_a ber'\xi+\ker\xi_a bei'\xi\}\end{matrix}\right]$	$\frac{P_t}{2\pi}\left[\begin{matrix}\{-bei\xi_a kei\xi+ber\xi_a \ker\xi\}\\ -\frac{(1-\nu)}{\xi}\{bei\xi_a \ker'\xi+ber\xi_a kei'\xi\}\end{matrix}\right]$
Mt	$\frac{P_t}{2\pi}\left[\begin{matrix}\frac{(1-\nu)}{\xi}\{kei\xi_a ber'\xi+\ker\xi_a bei'\xi\}\\ +\nu\{-kei\xi_a bei\xi+\ker\xi_a ber\xi\}\end{matrix}\right]$	$\frac{P_t}{2\pi}\left[\begin{matrix}\frac{(1-\nu)}{\xi}\{bei\xi_a \ker'\xi+ber\xi_a kei'\xi\}\\ +\nu\{-bei\xi_a kei\xi+ber\xi_a \ker\xi\}\end{matrix}\right]$

Where Mr is radial bending moment, Mt is circumferential bending moment, $l\left(=\sqrt[4]{\frac{D}{k}}\right)$ is characteristic length, $'=d/d\xi$, $\xi=r/l$, $\xi_a=a/l$,
ber, bei, ker, kei : Kelvin function
$P_t=2\pi aq$, P_t : Total ring load

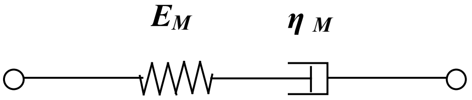

Fig. 18 Maxwell model

Viscoelastic Model of Ice

The stress-strain relation for ice could be represented by Maxwell's fluid model in Fig. 18, which shows almost same response as Burgers' model except for within one hour short creep. The material constants E_M and η_M are 28.5 t/cm^2 and 4.16 t/cm^{2}day, respectively determined from an experimental average value by Burgers' model (Jellinek and Brill, 1956).

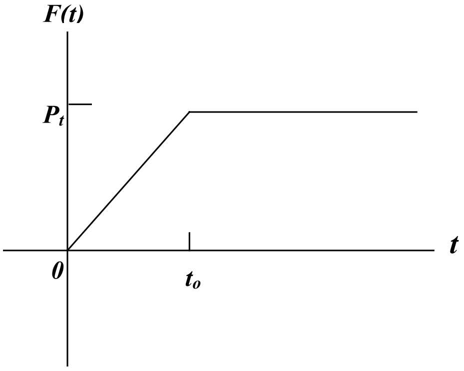

Fig. 19 Loading Time Function

Loading Time Function

The loading time history is represented by Fig. 19, which consists of the ramp loading during the construction and the constant load after the completion of Ice Dome. According to the experiences of 20m-span ice dome construction (Kokawa, 2001), 4 days can be adopted for t_o as the most speedy construction period.

Method of Viscoelastic Analysis

Assuming that ice is incompressible under hydrostatic stress and that it obeys Maxwell's model as mentioned before for deviatoric stress and strain, correspondence principle can be used for a linear viscoelastic analysis. The time dependent deformation and stress can be obtained from the inverse Laplace transforms after the substitution of $\nu=0.5$ and $E=\frac{3E_M}{2}\frac{s}{s+\mu}, \mu=\frac{E_M}{\eta_M}$ for the elastic solutions shown in the Table 2. The solution can be expressed by a kind of series in closed form after a long mathematical process, but these are omitted here for want of space.

Numerical Simulation of 20 m Span Ice Dome

Addition to the numeric data mentioned before such as the material constants and the construction period, P_t and h are adopted 100t (dead weight of the ice dome and snow live load are estimated, it corresponds to 318 kg/m^2 in the average horizontal loading) and 100 cm, respectively.
Referring to Fig. 20 and 21, very important results of the computation are obtained concerned with the stress relaxation and the flooding problem during 8 days.According to Figure 20, which represents the bending stress-time relation at the point (r=10m), the maximum creep stresses are very low compared to the elastic stresses. The reduction ratio is about 60 % from the elastic value in case of σ_r and

about 70 % in case of σ_t. It means that a big buoyant force takes place with time. The maximum σ_r : 1.74 kg/cm^2 corresponds to 17.4 % of the bending strength of an ice, so it may be no problem in the capacity of the bearing strength. However, according to Fig. 21, which shows the displacement-time curves at major points, it is predicted the flooding phenomenon will occur during the construction at the central part (r=0m) of the ice plate because the deflection exceeds 1/10th of the thickness. But in this situation, it seems that the flooding water will freeze into good quality ice because the flooding velocity 20-30 mm/day is very low. In addition to this analysis, a creep analysis after a very long period is developed using Newtonian viscosity model in order to get the bending strain. According to it, the strain after 3 months at the point (r=10 m) will attain 1.55%, which lie in the middle stage of secondary creep. From these theoretical investigations, 20 m span ice dome might be possible on a 100cm-thickness of lake-ice plate.

Conclusion

Snow has been generally considered to be a nuisance in the cold and snowy regions. However, as seen in this paper, snow becomes a useful structural material for the construction of the ice shell. As the ice is a translucent

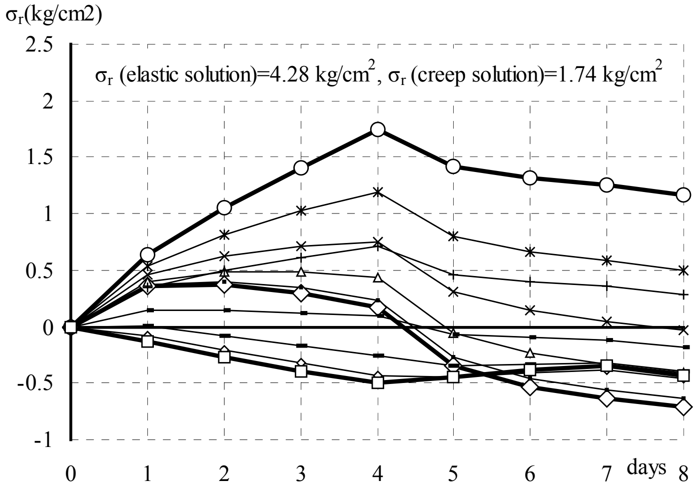

Fig. 20a σ_r-time curves (t_o=4day)

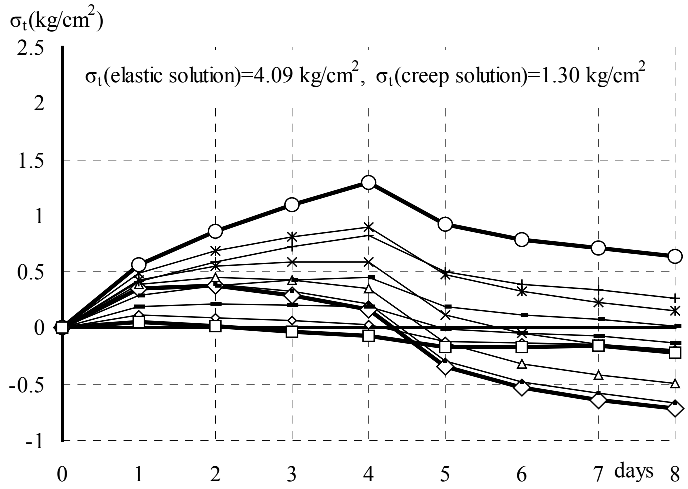

Fig. 20b σ_t-time curves (t_o=4day)

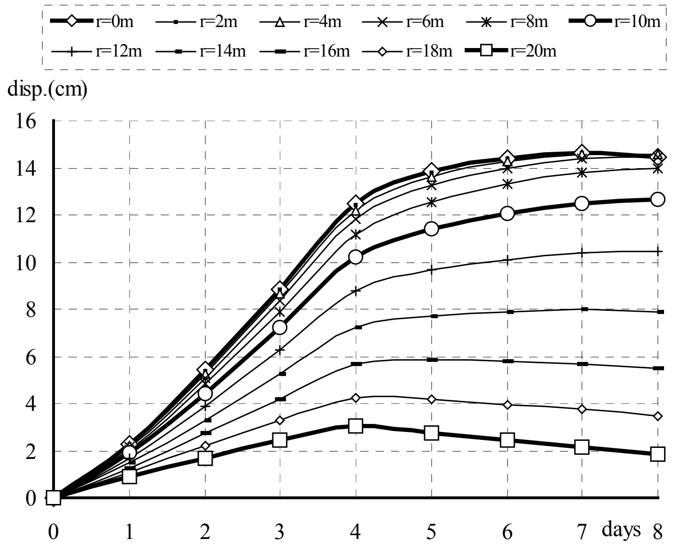

Fig. 21 Displacement-time curves (t_o=4day)

material, the ice shell creates a fantastic, beautiful space providing quite a unique built environment in winter. Particularly, in case of a large span, it will be more exciting artistically and getting more useful to apply to various kinds of architectural facilities for winter activity. It emerges in winter season, and disappears in summer. The ice shell is a very mysterious structure with nature.

Acknowledgements

The author wishes to thank the students of Hokkaido Tokai University since 1980, the members of Takasago Syuzou Company since 1987 and the members of Resort Management Company since 1997. The experiment of 30m-span ice dome was made possible by the financial supports from Keiryo Seikatsu Kaikan Grant in 2000 and by the membrane material supply from TO-RAY Ltd. Company.

References

Baudais D.J., Masterson D.M. and Watts J. S. (1974), "A system for offshore drilling in the Arctic Islands", J.Canadian Petroleum Technology, **13**, 3,15-26.

Jellinek, H. H. G. and Brill, R. (1956), "Viscoelastic Properties of Ice", *JOURNAL OF APPLIED PHYSICS*, VOLUME **27**, NUMBER 10, 1198-1209.

Kerr, A. D. (1976), "The bearing capacity of floating ice plates subjected to static or quasi-static loads", *J. Glaciology*, **17**, 229-268.

Kokawa, T. and Hirasawa, I. (1982/1983), "On the behavior of ice domes under short-term loading (in Japanese)", *Bull. Hokkaido Tokai Univ.*, **Vol.3/4**, 77-85.

Kokawa, T. (1983), "Experimental study on creep buckling collapse of ice domes with 60cm span (in Japanese)", *Japan NCTAM*, **33**,151-152.

Hirasawa, I. and Kokawa, T. (1984a), "On the creep behaviors of ice domes with 2m in diameter (in Japanese)", *Bull. Hokkaido Tokai Univ.*, **Vol.5**, 7-15.

Kokawa, T., (1984b), "Axisymetric creep buckling analysis of ice domes (in Japanese), *Bull. Hokkaido Tokai Univ.,* **Vol.5**, 17-24.

Kokawa, T. (1985), "Experimental Studies on Ice Shell in Asahikawa", *Cold Regions Science and Technology*, **11**, 155-170.

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

Kokawa, T. (1988), "Construction and Creep Test of 15-m Span Ice Dome", *Proceeding of IAHR Ice Symposium Sapporo*, 390-399.

Kokawa, T. and Watanabe, K. (1997), "Ice Shell-Contemporary "Igloo" or "Kamakura"", *Proc. of Structural Morphology Nottingham*, 286-292.

Kokawa, T., Itoh, O. and Watanabe, K. (2000), "Ice Shell-Review and recent application", *Journal of IASS*, **Vol.41** (2000) n.1, April n.132, 23-29.

Kokawa, T., Itoh O. and Watanabe, T., (2001),"Re-challenge to 20-m span ice dome", *CD-ROM IASS in Nagoya Symp.*(edited by Kunieda),TP187.

Kokawa, T., (2002), "Field Study of a 30-m Span Ice Dome", *Journal of IASS* **Vol.43** (2002)n.2,139,93-100.

Kubo, Y. (1980), Introductory Remarks on Iceological Engineering(in Japanese), Tairyusha, 42-90.

Michel B., Drouin M., Lefebvre L.M., Rosenberg P. and Murry R. (1974), "Ice Bridges of the James Bay Project", Can. Geotech.J., **11**, 599-619.

Nevel, D. E. (1966), "Time dependent deflection of a floating ice sheet", *Research Report **196**. Cold Regions Research and Engineering Laboratory,* Hanover, New Hampshire.

Timoshenko, S.P. and Woinoesky-Krieger, S. (1959), Theory of Plates and Shells, McGraw-Hill, London, 2_{nd}. ed.

Wyman, M., (1950), "Deflection of an infinite plate", *Canadian Journal of Research*, Ser. A, **Vol. 28**, 293-302.