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CHALLENGE TO 20-M SPAN ICE DOME

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INTRODUCTION

As seen in the examples of "igloo" by Eskimo and "kamakura" by Japanese, ice shells can be a suitable method for using ice and snow-ice as structural material, and may provide an efficient architectural solution to certain problemes in the snowy and cold regions.

The snow dome with 10-m span was constructed by blowing milled snow over an inflatable hemisphere by a Peter miller(1). Stanley and Glockner carried out at first an experimental creep study on reinforced ice domes with 2-m span produced by spraying water onto an inflatable membrane(2). However, a large span ice shell has not yet been produced because there still exists many problemes to be solved related to the structural safety and construction technique.

Based on the results of investigations in Asahikawa for the last several years(3), the authors tried for the first time to construct a full-sized ice dome with 20-m span during the winter of 1985.

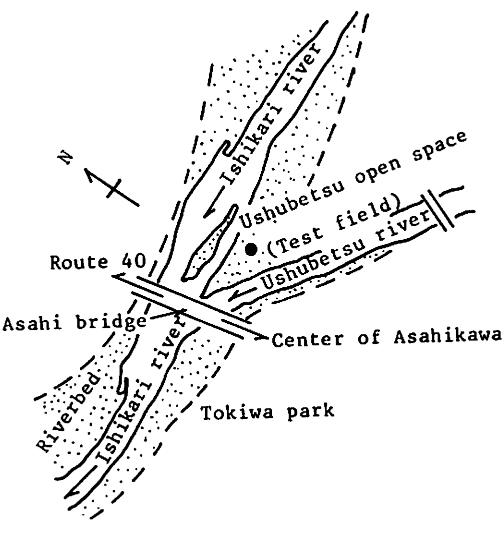


Fig.1 Location of test field

LOCATION OF TEST FIELD

Rising among the Taisetsu Mountains, four rivers flow through Asahikawa. Since water is a main structural material of ice shells, the authors had an idea that water should be pumped up from the rivers. Ushubetsu open space was selected for the field test, since it is located at the junction of the Ishikari river and Ushubetsu river, as shown in Fig.1. Asahi bridge, the oldest iron arch bridge in Asahikawa, spans near the riverbed, and the whole neighborhood had a nice view to be suitable for the construction of an ice shell as an environmental structure.

CONSTRUCTION METHOD

Foundation work

Assuming that inner pressure of the inflated membrane as a formwork is held at 7 cm water head; the total upward force acting to the snow-ice foundation becomes about 22 tons. On the other hand, the total weight of the foundation ring becomes 38 tons when density of the snow-ice is 0.85 g/cm^3, the sectional area 0.72 m^2(1.2m x 0.6m), central diameter 20 m, respectively. Polypropylen guy ropes were lashed to the rectangular timbers(45mm x 45mm x 3.6m) laid along the periphery with 20 m diameter and interbeded with the snow-ice foundation ring. The foundation 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 promptly. This operation was conducted during the three nights from January 14 to January 16. The compression force acts on the foundation ring under the application of snow and water onto the membrane because of the evulsion in the ropes. On the other hand, since the tension force acts on the ring after the construction, the timbers may be effective as reinforced members because the snow-ice is weak against the tension force.

Set of membrane and ropes

A nylon fiber PVC membrane(weight 360 g/m^2) bag was placed on the ground. This membrane is fabricated by welder along the periphery after wrapping in two pieces of plane sheets with 20 m diameter, and is easy to fabricate because there is no three dimensional cutting. According to the uniaxial test, all the membrane specimen were broken at the welder part, and their lowest limit value was about 10 kg/cm. When the inner pressure is 7 cm water head and the radius is 14.1 m, the membrane stress is about 5 kg/cm on the basis of membrane theory. Since the membrane is surrounded by ropes in this case, the stress becomes lower than 5 kg/cm and the membrane seems to be strong enough.

Each middle ropes were laid orthogonally on the membrane and connected with the guy ropes by the turnbuckles which could adjust the initial length of the ropes. Considering the needed rigidity and strength of the ropes, ϕ 14mm polypropylen ropes were used. According to the experimental study on the uniaxial test of the rope plus the turnbuckle system, the rope at the hook of the turnbuckle was broken, and its lowest value was 2.2 tons. Because the theoretical value of this system under construction is about 1 ton with maximum, this system seems to be safe enough. Rope spacing in each direction is 2.2 m. Ropes play an important role in not only forming the shape of the inflated membrane, but also giving the local curvature to increase the structural capacity.

Inflation of membrane

After the membrane was inflated roughly by three blowers(total air flow 115 m^3/min.), inner pressure was held at 7 cm water head by a boltex blower and a pressure controlling machine. On the way to inflate the membrane, the slip between the membrane and the ropes was observed.

Application of snow and water

A milled snow was blown onto the membrane by a rotary snowplow with the maximum throwing distance 15 m and the maximum blowing quantity of 90 tons/hour, and water pumped up from the Ishikari river was successively sprayed on the snow by an adjustable nozzle with the maximum spraying distance of 20 m and the maximum spraying amount of 0.45 m^3/min.. As a result of this operation, a snow-ice sherbet was produced on the membrane, and it was frozen hard some time later after cooling by cold outside air. In order to avoid imperfections, it is necessary during one blowing operation to keep milled snow depth to be thin. If it does not so, when water sprayed, only the surface part solidify and the membrane cannot keep the form because of the excessive weight, which cause material and geometrical imperfections. Since these imperfections reduce the structural efficiency of a constructed shell, this operation should be made carefully. However, a part of the membrane was depressed suddenly because of the excessive snow-ice sherbet, under the application of snow and water before dawn in January 19. This is due to the lack of experience in snowplow operating, due to the mechanical troubles caused by the severe cold in the night of January 17. In the before noon of January 19, the snow-ice at the depression part was removed by a hammer and scoops as shown in Fig.2. After the rest for two days, the operation of snow blowing and water spraying was started again at the night in January 21, and was repeated up to the desired shell thickness during the after three nights. Fig.3 shows the outside temperature during construction.

Removal of membrane and ropes

After the snow-ice froze and solidified, the membrane bag was deflated, as shown in Fig.4, and then the middle ropes and bag for reuse were removed. The construction of ice dome was then completed. However, judging from the fact that the inside light failed to transmit through the dome except the central part(3), the finish seemed to be inferior. In addition to the material imperfection at the boundary of the repaired region, both the material and geometrical imperfections were observed at another depression part including a bending crack with about 1 cm width, as shown in Fig.5.

Fig.2 Removal of imperfect snow-ice at depression part

Fig.4 Deflated membrane

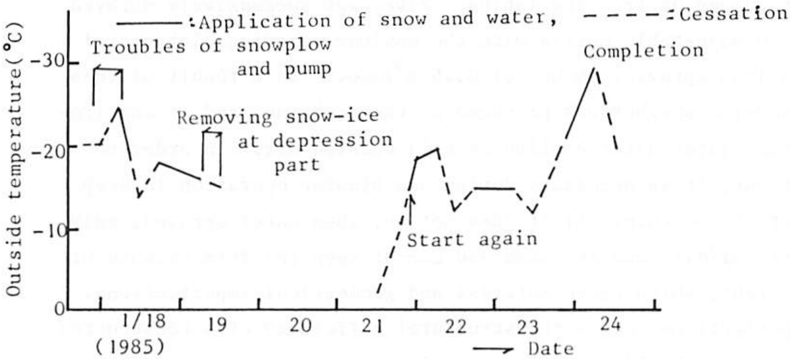


Fig.3 Outside air temperature under snow and water spraying

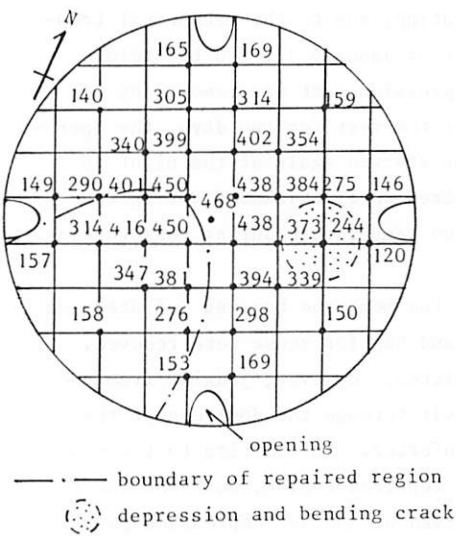


Fig.5 Heights(cm) at major points

Geometry of test dome

The heights at the major inside ropes intersecting points were measured before a creep test, as shown in Fig.5. The average observed value with respect to the heights at four intersecting points near center, 4.44m, was lower than the computed height by a simplified method(3), 5.06m. The reason of this disagreement seems to be due to the prescribed depressions caused by the excessive blowing snow depth during construction.

The distribution of the observed thickness did not become uniform because of unskilled snow blowing

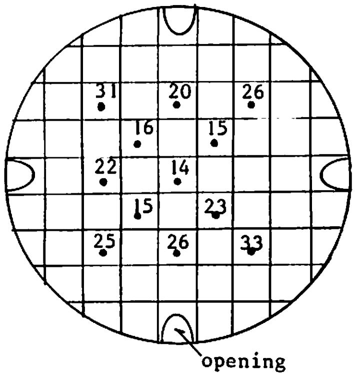
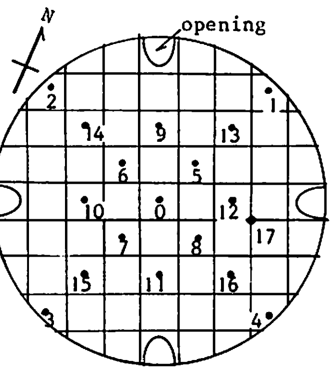
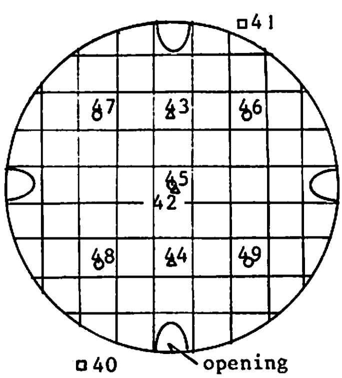


Fig.6 Thickness(cm) at major points



1-4;normal displacement
0,5-17;vertical displacement

Fig.7 Numbering points for measuring displacement



o;snow-ice temperature
△;inside temperature
□;outside temperature

Fig.8 Points for measuring temperature

during the construction, and central part was thinner than other parts, as shown in Fig.6.

CREEP TEST

Method of test

As shown in Fig.7, eighteen points for measuring displacements were prepaired at the inside surface of the test dome at the beginning stage. The displacement tranducers were used for all points. Where the displacements of point no.5 to 17 and 0 indicate vertical displacements, and that of point no.1 to 4 indicate normal displacements. The hanging method(3) was adopted so as to measure easily the vertical displacements.

Fig.8 shows ten points for measuring temperature at two points outside, three inside, and five snow-ice by copper-constantan thermocouples.

All displacements and temperatures were recorded automatically by a programmable data logger at adequate interval(2,3 hours) from the beginning to February 15. 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. According to meteorological data at Asahikawa Observatory Agency, the precipition from January 25 to February 27 was 61.5 mm, and this value corresponds to a load of 61.5 kg/m^2. Therefore, in this test the maximum snowfall load is considered to be about 1/3 th of the dead load.

Structural behaviour

The average of the outside air temperature during this February was -6.8 °C, and

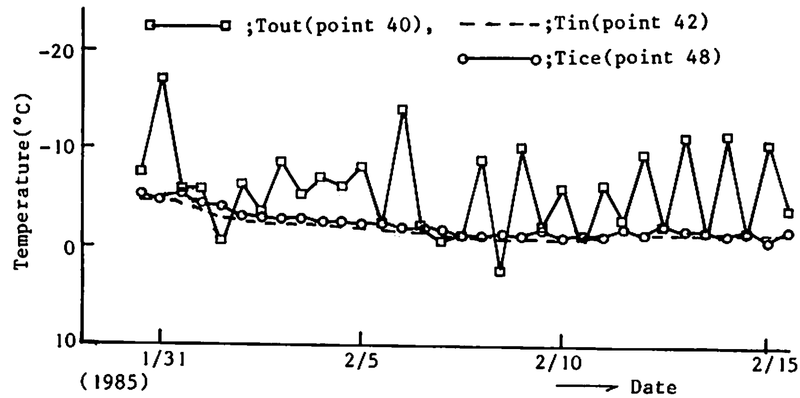


Fig.9 Temperature-time curves

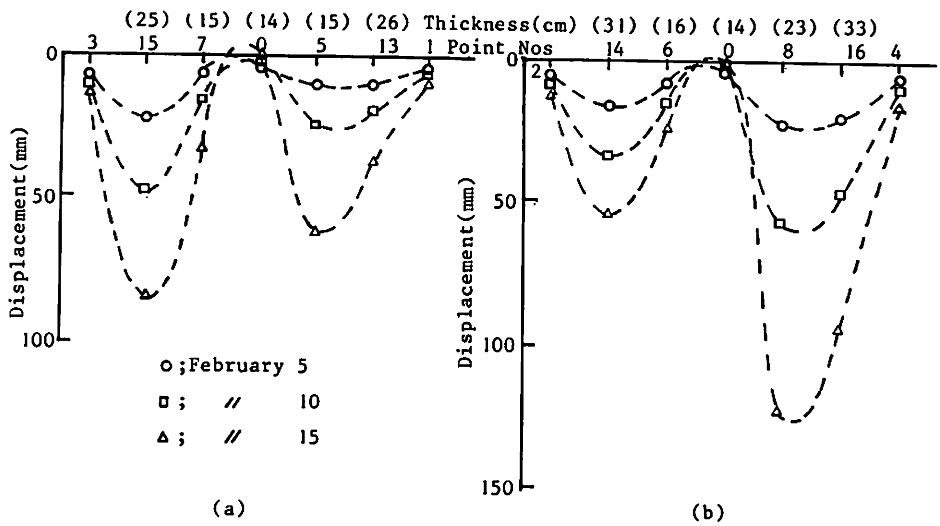


Fig.10 Deformations along two diagonal lines

it was milder than usual. Fig.9 shows three temprature-time curves. Tout, Tin and Tice indicate temperatures of outside air, inside air and snow-ice at representative points 40, 42 and 48, respectively. Under such condition that the openings are shut and dome has some snow cover in this test, Tin and Tice becomes about -2°C independently of Tout, due to the thermal insulation effect of the snow cover and the snow-ice.

Fig.10 shows the deformations along two diagonal lines in February 5,

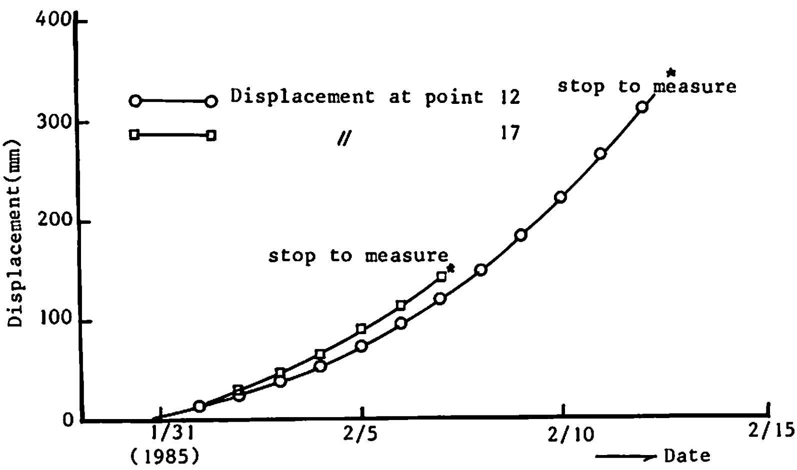


Fig.11 Displacement-time curves at depression part

10,15. They have preeminently symetric third mode with respect to the center and a little assymetric mode. Taking a broad view, the deformations grow linearly with time until February 10, and then accelerates gradually because of the increase in snow-load and the geometrical nonlinearlity. At the imperfection part where already the depression existed with bending crack of about 1 cm width at the completion, the width of crack was getting large and the deformation grew at an increasing rate without secondary creep stage, as shown in Fig.11. Due to the large deformation at this imperfection part shown in Fig.5, the test dome at last collapsed in February 27. The lifespan was very short than expected from the results of a creep study on 10-m span ice dome(3), and it was recognized that such an imperfection reduces steeply the structural integrity in shell. Therefore, it is important to construct ice shells without imperfections, and the blowing operation by snowplow must be carried out carefully.

CONCLUSIONS

This paper has described both the trial construction and the creep test of a 20-m span ice dome carried out in Asahikawa during the winter of 1985. The test dome was constructed at a riverbed as follows. 1) Inlating a membrane bag covered with ropes anchored to the snow-ice foundation circular ring. 2) Covering the membrane with thin snow-ice sherbet by blowing the milled snow with a rotary snowplow and spraying water pumped up from the Ishikari river. 3) Solidifying the snow-ice sherbet due to cooling by cold outside air. 4) Repeating 2) and 3) up to the desired shell thickness. 5) Removing the bag and ropes for reuse. Because the milled snow was blown onto the membrane too much during one blowing operation, the geometrical and material imperfections of the constructed dome was observed in some places. The operation of blowing snow depth to be thin is not so difficult, and could be improved little by little by some experiences. After construction, a creep test was carried out under dead and snow load, and its structural behaviour up to the collapse was examined. In spite of the above-mentioned imperfections, it was very ductile and took about one month to collapse. On the basis of the results of this test, with a careful blowing operation by a snowplow, it is concluded that the proposed construction technique satisfies the facility of a rapid, easy and economical construction of a large ice shell, and the production of 20-m span ice domes could be practicable fundamentally.

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