An Experimental Study on Impact Loads of the Sliding Snow from the Roof of the Large-Scale Membrane Structures

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SYNOPSIS

Recently, many large-scale membrane structures have been constructed in cold regions. When such large structures are constructed, the impact load from lumps of snow and ice that fall from the roof and strike the structure below are major problems in design, in addition to the weight of the snowfall that piles up on the roof. In this study, the authors quantified impact loads through experimentation with the objective of establishing a method for evaluating the impact load from lumps of snow and ice as a design snow load, in order to propose a technique for evaluating the impact load of lumps of snow and ice. As a result, it is proved that lumps of snow and ice have unique impact characteristics.

1. Introduction

Recently, many large-scale membrane structures have been constructed in cold regions. When such large structures are built, in addition to the weight of the snowfall that piles up on the roof and the weight and lateral pressure of the snowfall that piles up around the structure, the impact load from lumps of snow and ice that fall from the roof and strike the structure below, and measures to disperse this snow and ice, are major problems in design. Although the impact load from snow and ice has been mentioned in several civil engineering papers relating to avalanches, almost nothing has been reported regarding the impact load from snow and ice falling from the roofs of buildings. Even in the AIJ Recommendations for Loads on Buildings and accompanying explanatory notes published by the Architectural Institute of Japan, it is not clear how the impact load from falling snow should be evaluated as a snow load. In this study, the authors quantified impact loads through experimentation with the objective of establishing a method for evaluating the impact load from lumps of snow and ice as a design snow load, in order to propose a technique for evaluating the impact load of lumps of snow and ice.

2. Previous Study

This section will cover the aforementioned previous study conducted in this area. Nakamura et al.[1)] used an adjustable slope roof and a measuring wall made up of 0.3 m × 1.0 m pressure plates arranged vertically side by side to measure the impact load when a snow block struck the wall. Each pressure plate was supported at four points with respect to lateral force, two of which were provided with load cells. The results showed that the maximum impact load from falling snow is 7 - 20 kN/m^2, depending on the slope of the roof and the distance to the wall.

Furukawa et al.[2)] placed snow blocks with a cross-sectional area of 0.45 m x 0.45 m (0.2 m^2), length of 0.45 - 2.3 m and density of 0.1 - 0.6 t/m^3 on a slide, accelerating them to 6 - 16 m/s and causing them to strike a pressure plate measuring 1.2 × 0.9 m supported with three load cells, and recorded on an oscillograph the force applied to the supports. The experiment showed that the impact waveform for the snow block peaked in the first few hundredths of a second and then remained almost constant until ultimately attenuating to zero.

3. Mechanism of Impact Loads from Snow Blocks

The schematics[2)] in Figure 1 show the impact waveforms derived from impact tests for snow blocks in previous studies. The mechanism of impact loads from snow blocks derived from these previous studies can be explained as follows.

From the instant of collision until compression failure, the snow block is in an almost completely elastic state (status ① in Figure 1). Once compression failure occurs, however, the status switches to a direction of motion that is 90° with respect to the direction in which force has been applied, while forming a cone with apex angle approximately 90° and with the collision cross-section as the base

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(status ③). In this paper, the status from ② to ④ will be referred to as the collision cone formation process, while the status from (4) to the end of collision will be referred to as the fluid collision process. The maximum impact load Pm is derived from the failure strength of the snow block σ (N/m^2), and if the collision cross-section of the snow block is A (m^2), the maximum impact load is expressed as $Pm = \sigma A$ (N). It has been reported that the fluid collision load can be expressed almost perfectly by $P = \gamma V^2 A$ (N).

It has been reported[3)] that the failure strength of snow is 10 N/cm^2 for a density of $\gamma = 0.3$ g/cm^3, 30 N/cm^2 for a density of $\gamma = 0.4$ g/cm^3 and 150 N/cm^2 for a density of $\gamma = 0.5$ g/cm^3. Thus the failure strength increases dramatically as the density increases. However, this data is for an extremely low strain rate of 10^{-4} – 10^{-3}/sec. With very large structures such as domes, the collision sometimes occurs at a rate of 30 m/s, so the question remains as to whether this data is applicable. Also, in the case of actual falling snow striking an object, the edges of the lump of snow tend to failure and particles of snow are flung outward. As a result, the maximum impact load is thought to be different from the failure strength mentioned above.

4. Drop Impact Test Using Snow and Ice Blocks

4.1 Outline of test

To determine the maximum impact load from lumps of snow and ice under conditions near those of the actual phenomenon, a test was conducted in the city of Sapporo on Japan's northernmost island of Hokkaido. Photo 1 shows a view of the test scene. A ladder truck was used to drop snow and ice blocks from various heights. Load cells were used to measure the impact load, and a digital video camera was used to measure the drop speed.

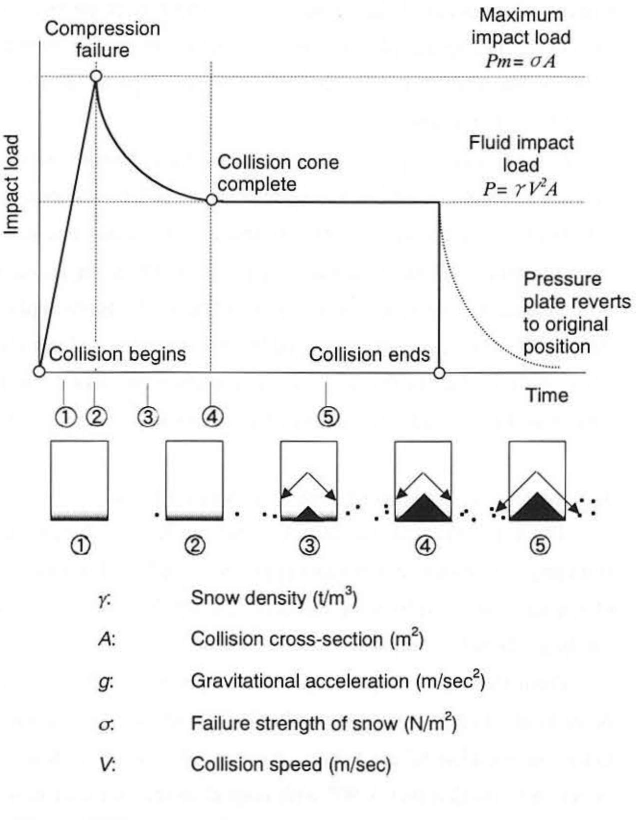


Figure 1 Waveforms for impact of snow and ice blocks and schematics showing status of blocks

The blocks of snow and ice used for the test were created by filling a 40 cm square mold with natural fallen snow two to three days after the snowfall, packing it to simulate compaction on the roof, and then leaving it outdoors for one day and one night when the temperature was below freezing. In addition, on the assumption that the snow would freeze in some cases, another block was also prepared by packing natural snow into a 40 cm square mold, and then running tap water in and placing the mold in a cold room at –15°C so it would gradually freeze. Using these blocks, the test was conducted under the conditions shown in Table 1. The snow and ice blocks were classified as follows by their density:

Low density block:

Snow density less than 0.3 g/cm^3

Medium density block:

Snow density equal to or greater than 0.3 g/cm^3 but less than 0.6 g/cm^3

High-density block:

Snow density greater than 0.6 g/cm^3

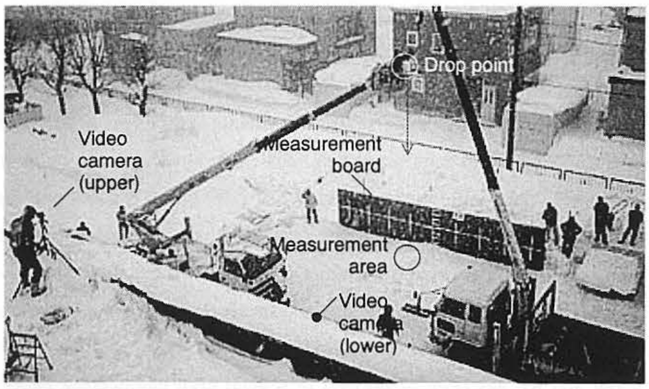


Photo 1 Scene of Experiment

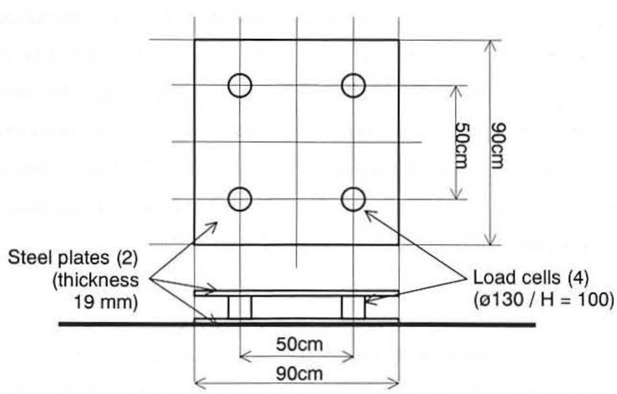


Figure 2 Outline of impact load measurement apparatus

Table 1 Specifications of measuring apparatus

Unit	Model No.	Specifications
Load cell (pressure gauge)	LUK-5TBS (quantity: 4)	Max. measurement load 5 tonf Measurement frequency range DC 2 kHz
Dynamic strain amp	DPM-611A (3-channel)	46 dB at S/N ratio of 1000 / 52 dB at other S/N ratios Measurement frequency DC 2.5 kHz
Data recorder	SPC-35	No. of measurement channels: 8 CPU: 98 NOTE SX/E40M Resolution: 16 bit (80 dB or greater) Maximum sampling frequency: 1 kHz

Table 2 Series of Tests

Drop height (m)	Snow density	Block size (cm)	No. of trials
2.5	Low		
	Medium	30sq. – 40sq.	4
	High	30sq.	4
5	Low		
	Medium	30sq.	
	High	30sq.	6
7	Low	40sq.	3
	Medium	20sq. – 40sq.	6
	High	30sq.	6
10	Low		
	Medium	30sq.	
	High	30sq.	4

Table 3 Test Results

Test No.	Test height (m)	Block size (cm)	Snow weight (kg)	Unit weight (g/cm3)	Impact load (kN)
2	2.5	40 sq.	28.3	0.44	17.1
1	2.5	40 sq.	30.2	0.47	24.9
3	2.5	40 sq.	31.7	0.50	18.2
20	2.5	30 sq.	15.2	0.56	8.5
23	2.5	30 sq.	17.6	0.65	12.8
21	2.5	30 sq.	19.2	0.71	12.3
22	2.5	30 sq.	20.2	0.75	11.9
19	2.5	30 sq.	20.9	0.77	21.1
4	5.0	30 sq.	17.9	0.66	11.8
8	5.0	30 sq.	17.9	0.66	22.1
5	5.0	30 sq.	18.1	0.67	12.1
6	5.0	30 sq.	18.3	0.68	11.1
9	5.0	30 sq.	25.4	0.94	27.5
7	5.0	30 sq.	26.3	0.97	21.7
24	7.5	40 sq.	15.0	0.23	8.3
25	7.5	40 sq.	15.0	0.23	8.6
26	7.5	40 sq.	15.0	0.23	9.3
28	7.5	40 sq.	30.7	0.48	23.3
29	7.5	40 sq.	31.7	0.50	42.7
31	7.5	20 sq.	4.3	0.54	10.2
33	7.5	40 sq.	34.5	0.54	35.5
27	7.5	40 sq.	34.7	0.54	35.4
32	7.5	20 sq.	4.4	0.55	6.3
30	7.5	20 sq.	4.8	0.60	6.0
12	7.5	30 sq.	16.7	0.62	15.2
13	7.5	30 sq.	17.8	0.66	30.7
14	7.5	30 sq.	20.9	0.77	34.8
10	7.5	30 sq.	21.0	0.78	19.5
11	7.5	30 sq.	21.7	0.80	18.9
18	10.0	30 sq.	18.4	0.68	33.2
17	10.0	30 sq.	20.8	0.77	32.1
16	10.0	30 sq.	25.0	0.93	30.4
15	10.0	30 sq.	25.1	0.93	21.6

4.2 Test Results

(1)Impact status of snow and ice blocks and impact waveforms

Figures 3 through 6 show the impact status and sample impact waveforms for the medium density and high density blocks. Due to the nature of the load cells, compressive force is shown as a negative number. This value varied depending on whether the part of the block that struck the plate was a flat surface or a corner. For both the medium density blocks and the high density blocks, the maximum impact load was greater when the block struck with a flat surface.

A comparison of the impact waveforms for the medium density block and high density block shows that the slope of the waveform immediately after impact was steeper in the case of the high density block. This is thought to be because the high density block has greater rigidity than the medium density block, so after impact the time until failure is shorter. In contrast, the medium density block only reaches failure deformation (the status after ② in Figure 1) after a certain degree of plastic deformation. In addition, even after the maximum impact load was achieved, the test result was sometimes a continuous curve with a single peak and sometimes a curve with several peaks at closely spaced intervals. This is thought to be due partly to the difference between flat surface collision and corner collision and partly due to variations in the configuration of the snow blocks. The snow blocks consist of an irregular arrangement of hard components and soft components, with each block having its own unique configuration, and this is thought to have resulted in some waveforms with one peak and others with two or more peaks. However, a common trend can be seen in the envelope waveforms (the dotted line in each figure).

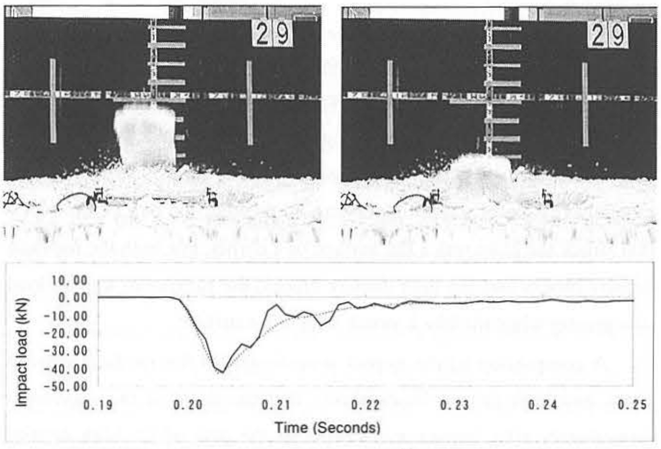
(2)Amount of energy and maximum impact load

A study of the impact load was made using the kinetic energy possessed by the snow and ice block immediately before impact, which is derived from the product of the mass and the drop height.

Figure 7 shows the relationship between maximum impact load and amount of energy. Although there are some variations, the overall trend shown is that, as the amount of energy increases, the impact load also increases. In addition, the values for the high density block are somewhat higher than those of the low and medium density blocks; however, some of the low and medium density blocks had values that approached those of the high density blocks. This is thought to be due to variations in the configuration of the prepared blocks, causing the snow in the impact surface of the low and medium density blocks to be near that of ice.

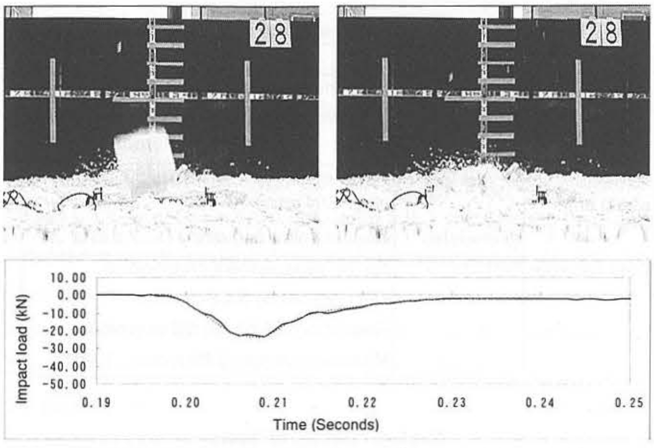
(3)Snow density and maximum impact load

Figure 8 shows the relationship between maximum impact load and density in this test data. Here the impact load was derived by dividing the measured value by the cross-sectional area of the dropped block. The collision speed in this test was 7 - 14 m/s. According to these results, the maximum value for impact load tended to increase until the density reached 0.6 g/cm^3, but remained at 40 N/cm^2 for density values exceeding 0.6 g/cm^3. Therefore, the value was lower overall than the failure strength with respect to low-speed compression.



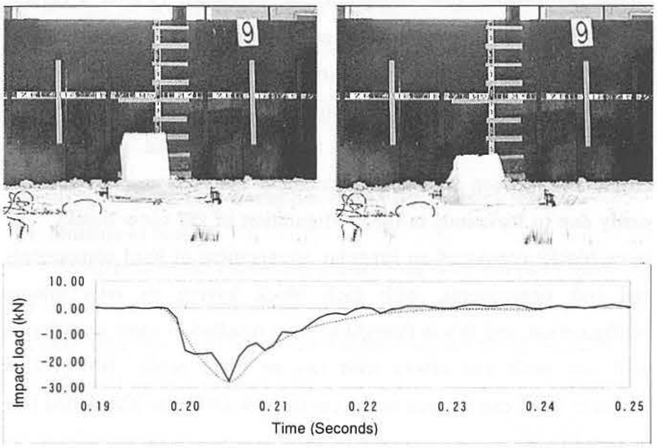
(Shape: 40 cm sq./Density: 0.50 g/cm^3/Drop height: 7.5 m)

Figure 3 Status of impact by flat surface of medium density block and impact waveform



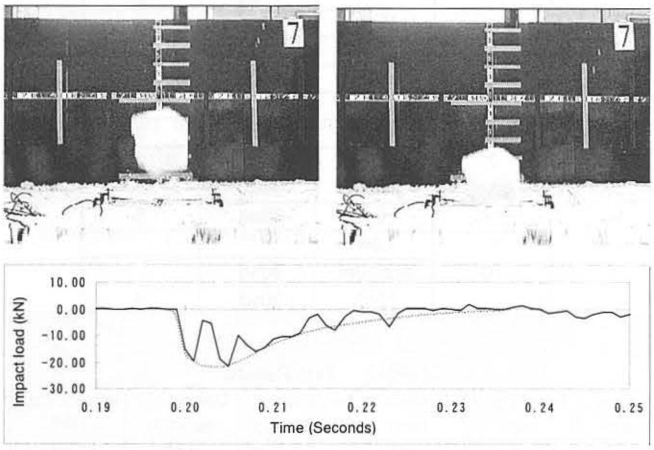
(Shape: 40 cm sq./Density: 0.48 g/cm^3/Drop height: 7.5 m)

Table 4 Status of impact by corner of medium density block and impact waveform



(Shape: 30 cm sq./Density: 0.94 g/cm^3/Drop height: 5 m)

Figure 5 Status of impact by flat surface of high density block and impact waveform



(Shape: 30 cm sq./Density: 0.97 g/cm^3/Drop height: 5 m)

Table 6 Status of impact by corner of high density block and impact waveform

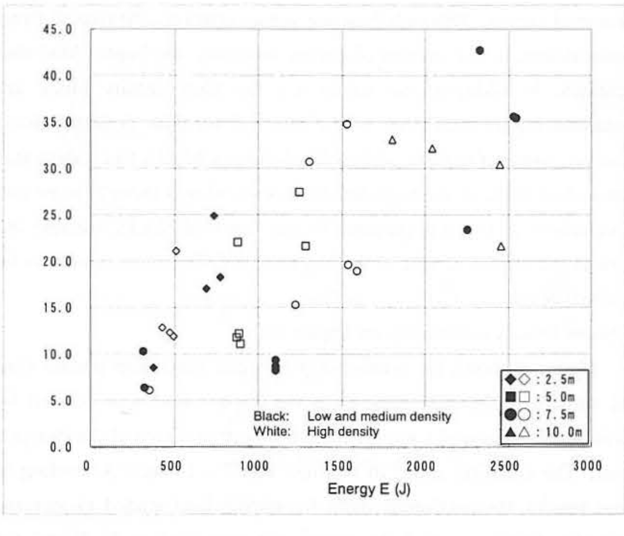


Figure 7 Relationship Between Energy and Maximum Impact Load

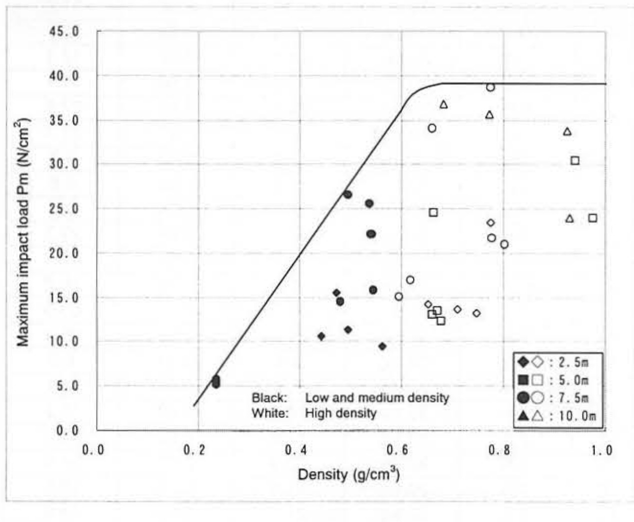


Figure 8 Relationship Between Snow Density and Maximum Impact Load

5. Method of Evaluating Impact Load of Snow and Ice Blocks

5.1 Current status of design method of impulsive load for structures [4)]

The current trend in shock-resistant design for structures is to replace impact load with static load and to use the allowable stress method to conduct the design. However, in actual design, no specific methods have been established for how the impact load should be replaced by static load.

In studies of such scenarios as an aircraft crashing into a nuclear power facility, the impact load of the aircraft is determined using a load-time curve and dynamic response analysis is conducted. Similar studies are done for the design of rock-sheds. Therefore, there is thought to be a need to clarify the dynamic response characteristics.

5.2 Characteristics of impact waveforms for snow and ice blocks

A comparison was made with the impact waveforms for other objects in order to determine the impact level and impact characteristics of snow and ice blocks. Figure 9 shows a comparison of impact waveforms. The waveform for the snow and ice block shown in this figure is for a block with a density of 0.78 g/cm^3, weight 21 kg and drop height of 7.5 m.

The waveform for sandbags is for the e20 kg sandbag used in the snow and ice block drop impact test in Chapter 4, dropped from the same heights as the snow and ice block (four times from a height of 3.5 m; four times from a height of 5.0 m; twice from a height of 7.5 m, and four times from a height of 10.0 m). The waveform in the figure is for an object dropped from a height of 7.5 m. A comparison of the waveforms for sandbags and snow and ice blocks shows that, due to the differences in their form, the sandbag had the greater impact load. This was true for the other trials as well.

The waveform for the rock[5)] shows the results when an EPS shock-absorbent material 2 cm thick was placed over the load cell and a 100 kg weight was dropped so impact occurred at a speed of 3 m/s. The momentum was about the same as for the snow and ice block and the sandbag. It is predicted that, if no shock-absorbent material were used, the time of impact would be even quicker, and the maximum impact load would be even greater.

Figure 9 also includes the impact load for a fluid of the same density as the snow and ice block. From these results, it can be seen that the impact load for the snow and ice block is between that of a fluid and a solid. Moreover, extremely hard objects such as the rock have a short impact time and a large peak value, whereas viscoelastic objects such as the snow and ice block have a comparatively long impact time and a gradual curve. These are the special characteristics of impact by snow and ice blocks.

6. Conclusion

This study concerned a field experiment conducted to determine the impact load of falling lumps of snow and ice, for which no evaluation method has been determined. The tests found that the impact waveforms for snow and ice blocks peaked immediately after impact, and that the maximum impact load varied greatly depending on the density and the collision speed.

The tests also revealed that lumps of snow and ice have unique impact characteristics, with an impact load duration of 0.02 - 0.03 seconds. Since this differs greatly from the primary natural period for ordinary structures, snow and ice are thought to exhibit behavior that differs from the results of static analysis. Accordingly, a study using dynamic response analysis is needed.

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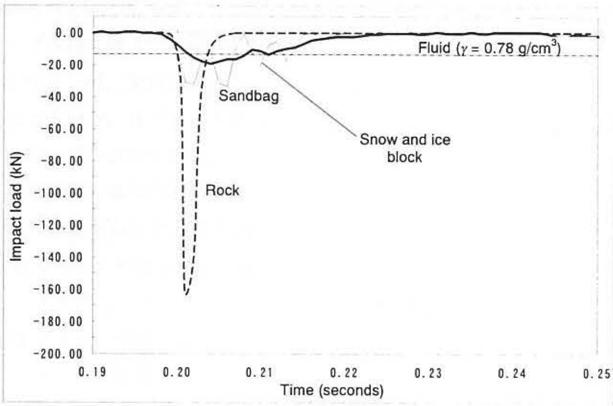

(Snow and Ice Block Trial: Test No. 10)

Figure 9 Comparison of Impact Waveforms for Various Objects

大規模膜屋根構造物における屋根上落雪による衝撃荷重に関する実験的研究

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梗　　概

近年、寒冷地において多くの大規模な膜屋根ドームが建設されている。このような大型施設の場合、屋根から落下する雪氷塊が下方の建築物に衝突する衝撃荷重およびその飛散対策などが設計時の大きな問題となる。しかし、雪氷塊の衝撃荷重については、土木分野の雪崩に関するものが幾つか文献に記述されているが、建築物で発生するような雪氷塊落下による衝撃荷重に関する記述は殆ど見られないのが現状である。本研究では、実験等から雪氷塊の衝撃荷重の定量化を図り、設計用積雪荷重としての考え方について報告する。

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