Simulation of Compressive 'Cone-Shaped' Ice Specimen Experiments using LS-DYNA®

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Abstract

A laboratory scale compressive cone-shaped ice experiments were performed, and a numerical simulation model using LS-DYNA was developed. Modified material properties were applied based on a crushable foam model (MAT 63) as the ice properties. To simulate a saw-tooth pattern which is commonly observed through experiments in ice, an additional function of failure criteria, which is maximum principal stress, was included. Results of the experimental and numerical simulation were compared and represented a good agreement. The proposed numerical simulation model was extended to a larger scale and verified.

Introduction

A simulation of ice-structure interaction using finite element software has been performed by many researchers. Carney et al. [2] conducted a numerical simulation between the space shuttle and ice block in circumstances of high strain-rate impact. The numerical ice model was introduced and verified by experimental results. Hilding et al. [7] performed a numerical simulation of the situation where the ice piles up in front of a lighthouse beneath the ice sheet using a cohesive element method (CEM). Comparison between experimental data and numerical analysis were similar quantitatively and qualitatively. Gagnon and Derradji [3], Gagnon [4]-[6] obtained a practical ice material property using crushable foam model on the basis of the bergy-bits field trial test with the CCGS Terry Fox icebreaker and applied in numerical analysis. The results of numerical simulation using calibrated volumetric strain-stress relation demonstrated a clear agreement compared to field trial data.

Since, most of the numerical model developed by an individual study tends to satisfy a certain test condition. This means that the capability of expansion into a diverse scenario was not considered. In that sense, the suggested numerical simulation model may not apply for other conditions. Therefore, the applicability of the suggested numerical simulation model is still in question. In addition, most of the numerical simulation models were developed in case of the impact situation which means that the strain rate is relatively high. In reality, the actual ice loading conditions are distributed in a low to high strain rate condition. Therefore, there is a high demand for developing a numerical simulation model which can be applied in diverse conditions.

This study aimed to develop a numerical model and material properties of the ice that can be applied for the low to high strain rate without any restriction using LS-DYNA. Validation of the proposed numerical ice model was verified based on the compressive ice test results done in the cold room using a 10cm diameter cone-shaped ice specimen. Furthermore, the verification process for scalability was performed by applying a developed numerical simulation model to the larger scale ice sample (25cm diameter).

Numerical Ice Model

Gagnon's ice model:

Material properties of ice, which included a volumetric strain-stress relationship, based on a crushable foam model (MAT_63) were calibrated by Gagnon [3]-[4] through the bergy-bit field trial experimental data. For the numerical simulation, LS-DYNA was chosen and crushable foam was applied as the material model. Behavior of the ice model using crushable foam is dominated by the volumetric strain-stress relationship. This means that defining a proper volumetric strain-stress relationship is the most important aspect in numerical simulation using crushable foam. Figure 1 shows a suggested volumetric strain-stress relationship by Gagnon.

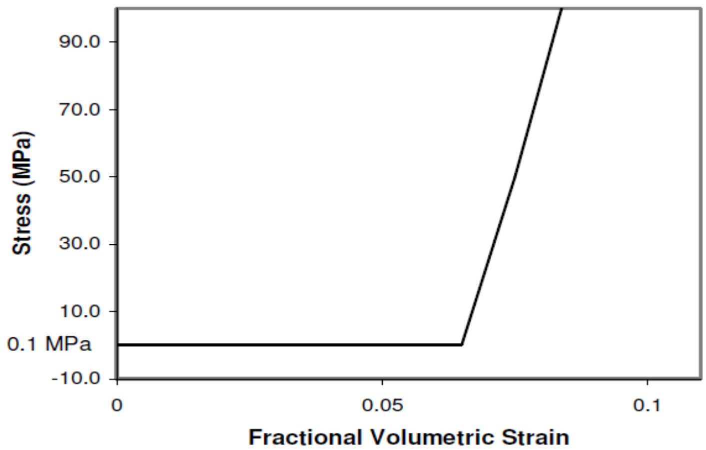


Figure 1: Volumetric strain-stress relationship [3]

Gagnon [5]-[6] applied an updated methodology to simulate a saw-tooth pattern, which is commonly observed in the majority of the ice experimental performance, in respect of force-time history. The finite element model was composed by a several layer and different material properties were assigned to create a 'forced' saw-tooth pattern during a numerical simulation (figure 2).

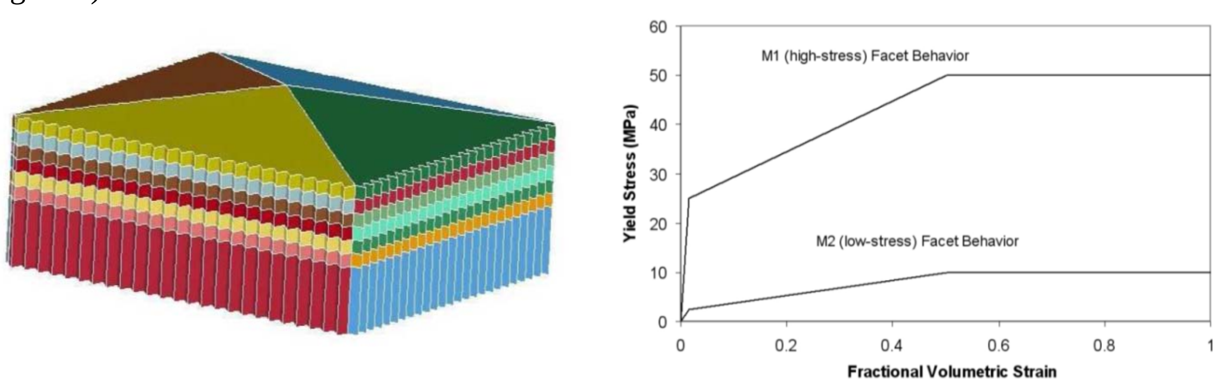


Figure 2: View of the numerical model (left), volumetric strain stress curves for crushable foam (right) [5] [6]

Proposed ice model

In this study, a force-displacement history, which is similar to the experimental results, was implemented by applying the modified volumetric strain-stress relationship. To simulate the saw-tooth pattern during a numerical simulation, 'maximum principal stress' failure criteria was added additionally along with the same ice model properties (Bjerkås, [1]). Table 1 shows a material properties and the failure criteria applied in this study.

Table 1: Ice material properties and failure criteria

	Density (kg/m3)	Young's modulus (GPa)	Poisson's ratio	Tensile Cut-off Stress (MPa)	Max. Principal Stress Criteria (MPa)
Ice material 1	900.0	9.0	0.003	35.0	35.0
Ice material 2	900.0	9.0	0.003	15.0	15.0

For the contact option, an element eroding option, *CONTACT_ERODING_NODES_TO_SURFACE, was set up to eliminate any elements automatically that reached the defined failure criteria. This add-on option was adopted to reflect the ice spalling event during the experiment.

Similar to Gagnon's simulation methodology, the ice model was separated into two different parts (assigned two different Part ID during a simulation) to reflect the high pressure zone at the center that was commonly observed through the experiments. Ice model properties for each part were assigned differently, so that a high pressure zone can be distributed at the center of ice model as intended.

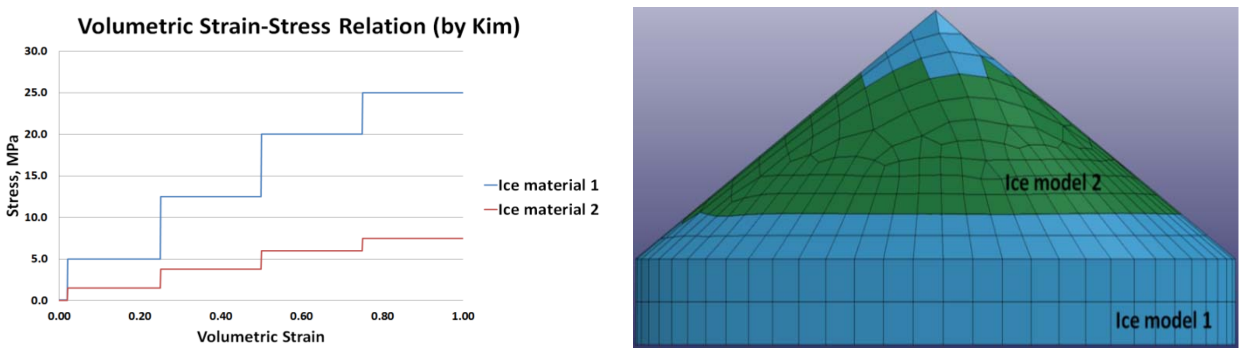


Figure 4: Volumetric strain-stress relation of crushable foam (left), layer of ice model (right)

Figure 5 shows the numerical simulation model. 6-dof fixed boundary condition was applied at the ice cone bottom to implement the conditions attached to the universal testing machine (UTM). A steel plate attached on the top of UTM is moving downward at a specified velocity. Two body contact simulation was performed. The material property of the steel plate was applied as a rigid body because prepared steel plate was thick enough to be considered as rigid and there was no visual deformation on the plate side during the test.

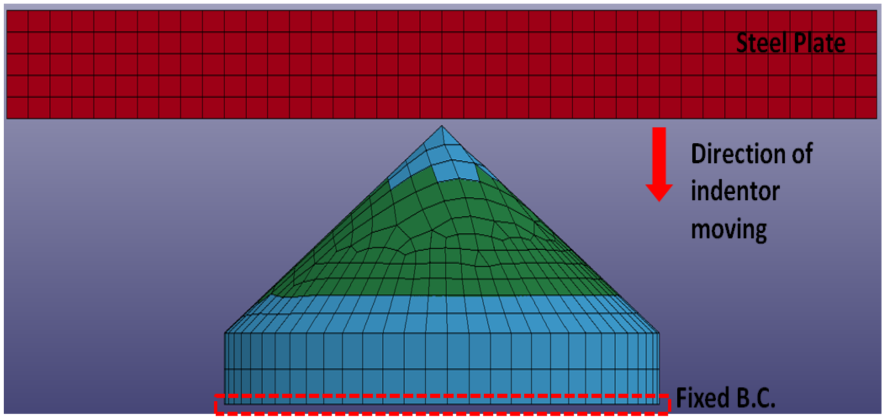


Figure 5: Numerical simulation model consist of ice specimen and steel plate

Results

The numerical simulation model developed in this study was verified compared with experimental results performed in the cold room. A 10cm diameter cone-shaped ice specimen was chosen for the test. Table 2 represents the specific experimental conditions. The temperature in the cold room was not considered during the numerical simulation. Figure 6 shows test set-up of 30° ice cone sample mounted at the UTM in the cold room.

Figure 6: Test set-up (left: 30° ice cone, right: 50° ice cone)

Table 2: Test condition (10cm diameter ice cone)

	Cone angle (°)	Test speed (mm/s)	Cold room temp. (°C)
Test 1	30	1	-5
Test 2	30	100	-5

The main focus of developing a numerical simulation model was to create a model that can be directly applied to a diverse condition such as different strain-rate or ice specimen size as discussed. In other words, the aim was to create a numerical simulation model that could be used in multiple conditions without any modification of ice material properties or simulation conditions. Figure 7 and 8 shows the comparison result of force-displacement curve between the proposed numerical simulation model and experimental results. Similarities between numerical simulation and experimental results can be identified in terms of qualitative and quantitative perspectives.

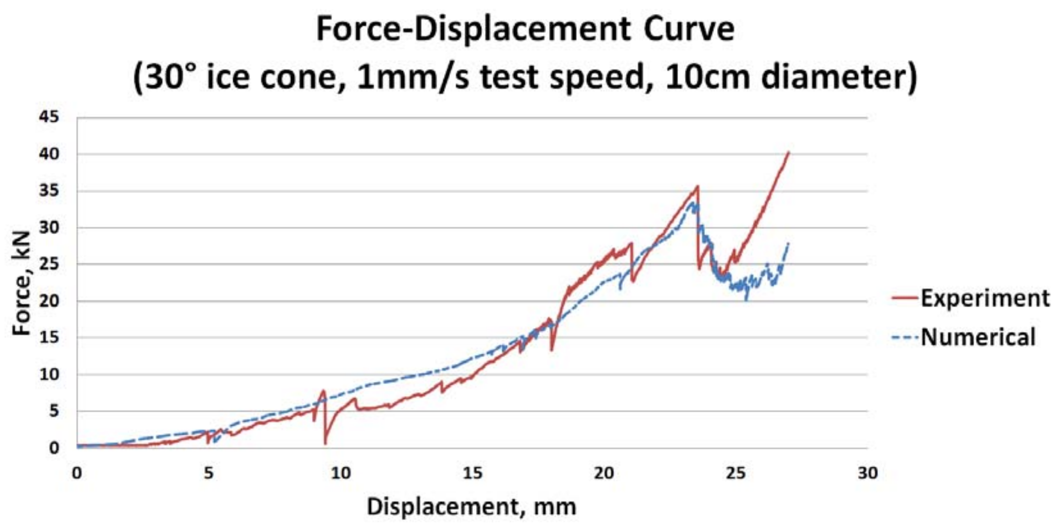


Figure 7: Comparison of force-displacement curve (1mm/s test speed)

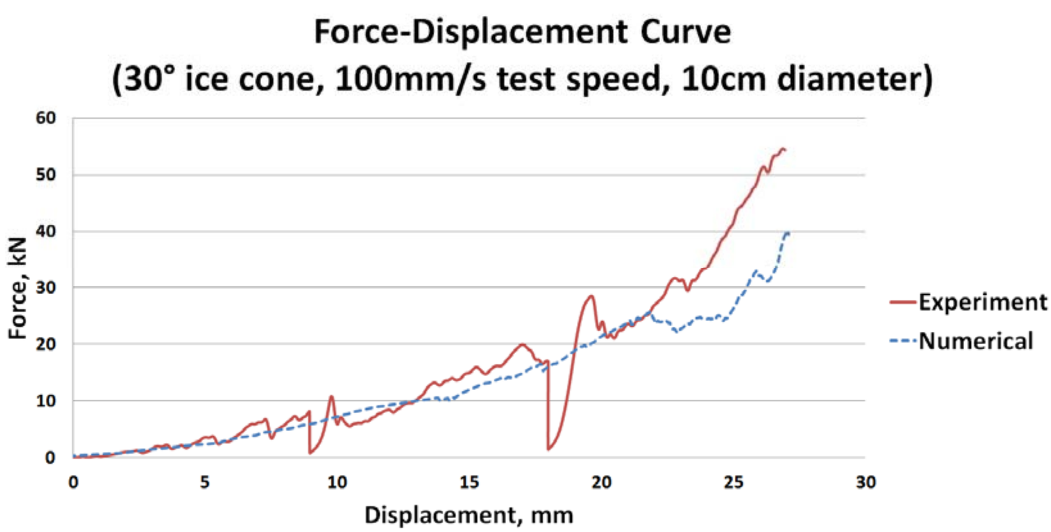


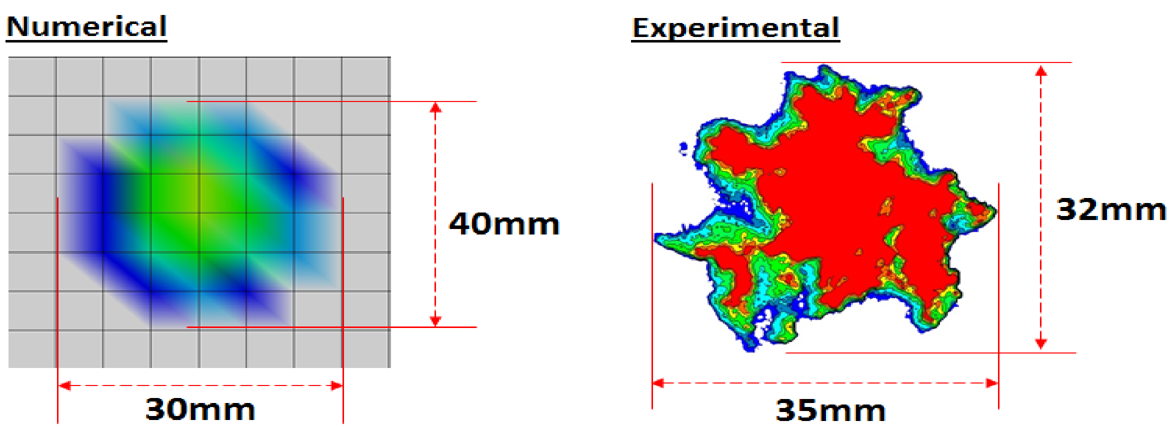
Figure 8: Comparison of force-displacement curve (100mm/s test speed)

The low speed test (figure 7) shows a good agreement relative to the high speed test (figure 8). This is because that typically spalling event occurs more often at the high speed test compared to the low speed test. The numerical simulation has not implemented a complete spalling which identified in the experimental result in case of the high speed test as shown in Fig. 8; however, the overall results of numerical simulation models showed a similar trend.

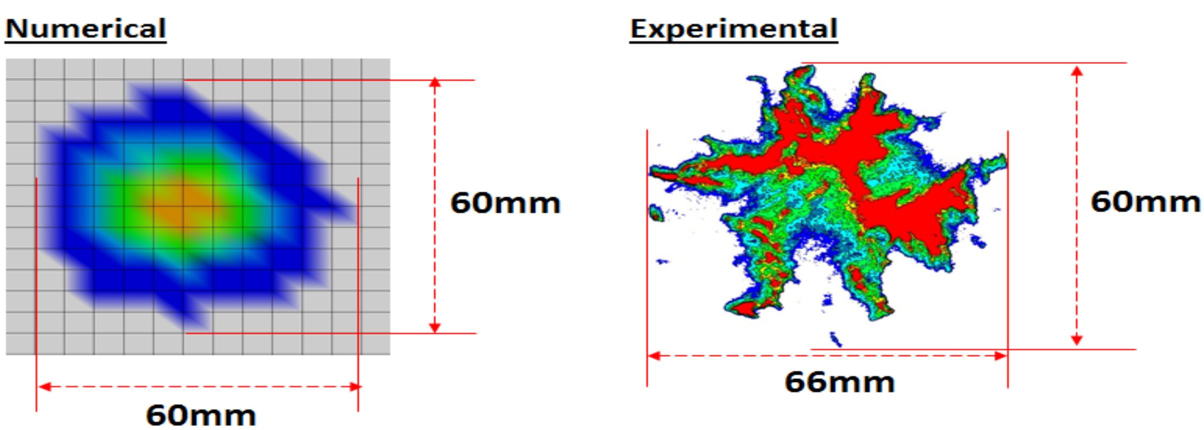
As shown in figure 8, the ice load at a certain displacement, at 9mm and 18mm, varies dramatically within a certain range. This is because this experiment was done as a ‘stepped’ crushing method instead of ‘straight’, so variation in the certain range (9mm and 18mm in this case) was caused by the discontinuity of the obtained data rather than caused by the experiment (Kim et al. [8]). Therefore, a comparison between numerical simulation and experimental results may become similar qualitatively if the curve is assumed to be continuous.

As mentioned, numerical simulation results indicated a good agreement in respect of global load. In addition, a comparative assessment of the local load was performed by comparing the 'spatial' pressure distribution at each test steps. The following figure 9 represents the results of spatial pressure distribution at each designed step. A spatial pressure distribution of experiment plotted in figure 9 was obtained by usage of the pressure measurement film.

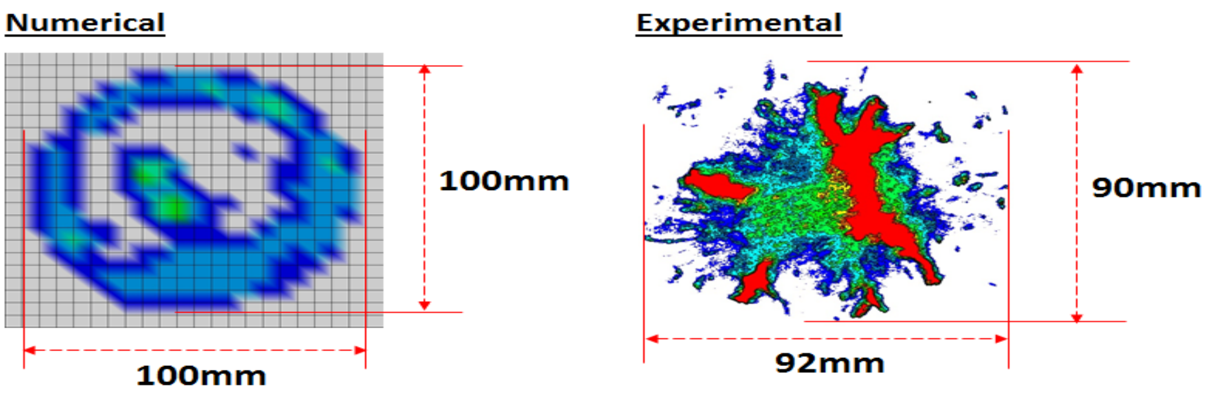
A separate segment set was defined through a numerical simulation on the contact surface of the structure side to obtain the 'interface pressure', and the results were applied for the comparison.



(a) Spatial pressure distribution at test step 1 (at displacement=9mm)



(b) Spatial pressure distribution at test step 2 (at displacement=18mm)



(c) Spatial pressure distribution at test step 3 (at displacement=27mm)

Fig. 9 Spatial pressure distribution plot (100mm/s test speed)

As shown in figure 9 (a), spatial pressure distribution in the first step represents a similar result (high pressure appeared at the center). However, difference of spatial pressure distribution between numerical simulation and experimental results become larger as test step progresses. This result can be explained in terms of two aspects.

First, the time period of spalling events of ice did not coincidence with numerical simulation and experimental result. In addition, size of the spall was not identical, even the failure criteria option was adopted to simulate spalling events. This induced the difference of the shape of the contact surface between two bodies. Second, characteristics of pressure indicating film induced the difference as explained by Kim et al. [8]. This means that spatial pressure distribution obtained through experiments may have been overestimated.

Application to Larger Model

Verification of the applicability of developed numerical simulation model into a larger model without modification was conducted. Test results done in the cold room using a 25cm diameter cone-shape ice specimen against a flat indentor were selected for the comparison. In addition, a concave shape indentor (conical shape as shown in figure 10) was also applied for the verification. Test conditions for each test were shown in Table 3.

Figure 10: 10° conical shape indentor

Table 3: Test condition (25cm diameter ice cone)

	Indentor shape	Indentor angle (°)	Cone angle (°)	Test speed (mm/s)
Test 1	Flat	-	25	1
Test 2	Conical	10	25	100

To evaluate the scalability, an identical numerical simulation model was applied without any modification. Force-displacement curves are shown in figure 11 and 12. In addition, it can be observed that the trends of simulation results are well reflected by the experiments; even the shape of the indentor was not a simple flat surface.

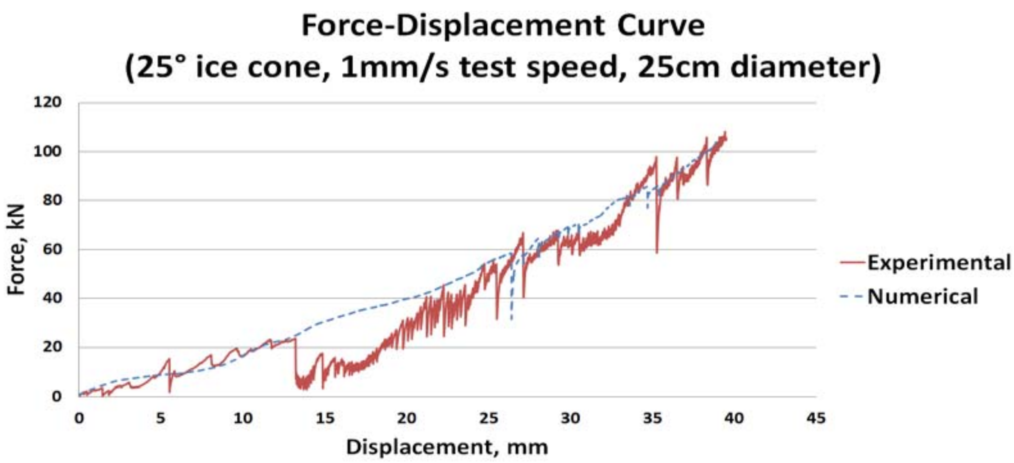


Figure 11: Comparison of force-displacement curve (25cm ice cone, 1mm/s test speed)

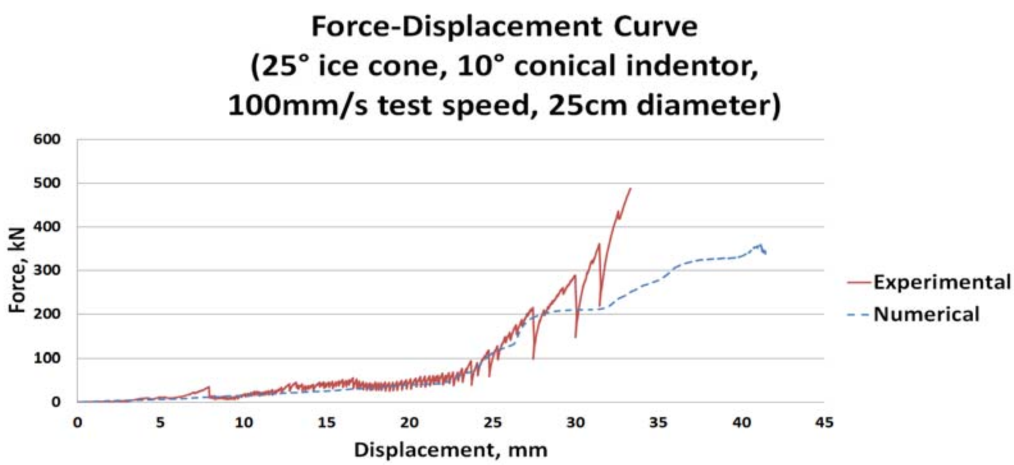


Figure 12: Comparison of force-displacement curve (25cm ice cone, 1mm/s test speed)

All of the details of spalling events were not captured by the numerical simulation (compared to small scale ice cone), unlike real experiments. However, as shown in figure 11 and 12, comparison results of the 25cm diameter ice specimen represented a good agreement in terms of quantitative and qualitative aspects. These results confirmed that the proposed numerical simulation model can be expanded.

Conclusion Remarks

In this study, a numerical simulation model of the cone-shaped compressive ice test was developed using LS-DYNA. Updated crushable foam material properties and failure criteria was applied to simulate the behavior of ice observed close to the actual experiments done in cold room. The applicability of the proposed numerical simulation model was verified respect of a global load. In addition, the spatial pressure distribution was also reviewed.

The evaluation of the scalability of the proposed numerical simulation model in this study was conducted and validated. Based on this applicability of the proposed numerical simulation model, a series of numerical simulations can be conducted considering various parameters and variables to investigate the influence of diverse condition.

References

[1] Bjerkås, M., 2002, Two failure criteria in common use for ice-structure interaction simulations, *Project report in "DIB 7989 Non-linear finite element methods-basic principles", Norwegian University of Science and Technology (NTNU)*, p. 18.

[2]Carney, K.S., Benson, D.J., Bois, P.D. and Lee, R., 2006, A high strain rate model with failure for ice in LS-DYNA. *9th International LS-DYNA Users Conference*, Dearborn, MI USA June 4-6.

[3] Gagnon, R.E., Derradji-Aouat, A., 2006, First results of numerical simulations of bergy bit collisions with the CCGS Terry Fox Icebreaker. *Proceedings of IAHR 2006*, Sapporo, Japan.

[4] Gagnon, R.E., 2007, Results of numerical simulations of growler impact tests. *Cold regions science and technology*, 49 (2007) pp.206-214.

[5] Gagnon, R.E., 2010, Numerical rendition of ice crushing. *20th IAHR International Symposium on Ice*, Lahti, Finland, June 14-18.

[6] Gagnon, R.E., 2011, A numerical model of ice crushing using a foam analogue. *Cold Regions Science and Technology*, 65 (2011) pp.335-350.

[7] Hilding, D., Forsberg, J. and Gürtner, A., 2011, Simulation of ice action loads on off shore structures. *8th European LS-DYNA Users Conference*, Strasbourg, May 2011.

[8] Kim, H., Daley, C., and Ulan-Kvitberg, C., 2012. Reappraisal of Pressure Distribution Induced by Ice structure interaction using high-precision pressure measurement film. *IceTech 2012*, Banff, Canada.