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FLUID-STRUCTURE-INTERACTION ANALYSIS OF AN ICE BLOCK-STRUCTURE COLLISION

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ABSTRACT
Due to climate change, production and transportation routes in Arctic regions are becoming more prevalent. When operating in Arctic waters, there is a significant risk of high energy encounters with smaller ice masses such as bergy bits and growlers. This study focuses on the structural response to high energy encounters in the surrounding water. The aim of the present work is the experimental validation of the Fluid-Structure-Interaction (FSI) technique of the LS-DYNA code, which enables us to analyze the response of colliding bodies considering the surrounding seawater. Numerical simulations of a collision between an ice block and a floating structure have been carried out using the FSI analysis technique of the LS-DYNA code for a more realistic and accurate prediction of the impact loadings. To verify the fluid modelling in LS-DYNA, analyses were performed to determine the added mass coefficients for a spherical body and a rectangular block. The coefficients were compared to the added mass coefficients calculated in WADAM with the same geometry. The simulation results were compared with laboratory experiments where a floating structure was impacted with an approximately one ton ice block at a speed of 2 m/s. The impacted structure was treated as a rigid body. The ice behavior was modeled using the elliptic yield criterion and the strain-based pressure dependent failure criterion for granular freshwater ice proposed by Liu et al. (2011a). The results of the numerical simulations compared favorably with actual experiments using freshwater ice blocks. The simulation produced reasonable values for the acceleration and load values, similar to those obtained in the laboratory experiments. The acceptable compatibility of the results proves that the FSI technique can be applied to the analysis of ship-ice collisions.

INTRODUCTION
The Arctic waters are becoming attractive due to their large reservoir of oil and gas. Explorations in such areas will meet with harsh environmental elements, such as ice loads and low temperatures. The sea ice extent and its thickness have diminished over recent years due to global warming. This diminishing ice may provide access to new sailing routes in these waters in the years to come. The probability of collisions between ships and ice floes, including growlers and bergy bits, may increase due to this increased activity. The assessment of loads caused by growler impacts is an important issue for ship designers.

Liu et al. (2011a) developed a material model for iceberg ice based on the plasticity theory, and the "erosion" technique was employed to simulate the crushing of the iceberg. Based on the simulated results of a collision between a fore ship structure and an iceberg obtained using the nonlinear finite element method, Liu et al. (2011b) further adopted the Bayesian networks method to estimate the iceberg impact loads on the fore ship and the corresponding damage. The impact energy of the ship-iceberg collision and the damage originated in the ship's structure were assessed. Kim et al. (2012) proposed an experimental setup of laboratory-scale collisions with ice masses for the Aalto Ice Tank. A sensitivity study of the nonlinear solution for the problem of the ice vs. rigid plate collision was presented. Gagnon and Derradji-Aouat (2006) have carried out both experimental and numerical work on growler impacts. The so-called "crushable foam" material type was adopted to simulate ice crushing (Gagnon, 2011). A large number of studies have been reported in the literature, but fluid-structure-interaction (FSI) during collision has been the subject of only limited research. FSI is of great importance because this computational technique allows the treatment of problems such as ice impacts due to wave-induced motions and realistic simulations of operations in the marginal ice zone. A number of research studies have used the LS-DYNA code, in which FSI problems are treated by a moving mesh algorithm, the overlap capability of the grid to the structural mesh using the multi-material Arbitrary Lagrangian-Eulerian (ALE) formulation and the Euler-Lagrangian coupling algorithm (LSTC, 2011). Lee and Nguyen (2011) carried out an advanced study to estimate more realistic and reliable bow shoulder and side collision responses between a liquefied natural gas carrier (LNGC) and a cubic iceberg using the FSI analysis technique of the LS-DYNA code. The iceberg was affected by the wave-making of the LNGC in addition to the LNGC's and iceberg's motions in the water, especially the relative drift velocity of the iceberg that was induced by the squeezing pressure of the water layer entrapped between the iceberg and the LNGC. The first simulations of a collision between a bergy bit and a loaded tanker that included hydrodynamics, a crushable foam ice model and damage to the vessel were performed by Gagnon and Wang (2012). The results show realistic grillage damage characteristics. The numerical simulations using the FSI technique have been directed towards producing realistic wave patterns and ice motions/forces. The performance of the ice model is often validated. However, ALE analysis with LS-DYNA is far from straightforward, and it is important to verify that the fluid model in LS-DYNA provides accurate results.

In this study, numerical simulations of a collision between an ice block and a floating structure were carried out using FSI analysis with LS-DYNA. To verify the fluid modelling in LS-DYNA, analyses of the added mass coefficients for a spherical body and a rectangular block were compared with the coefficients calculated using the potential flow solver WADAM. To verify the method, the analysis of laboratory experiments of an ice-structure collision considering the surrounding seawater was carried out.

EXPERIMENTAL SETUP

The tests were conducted in a 40 m by 40 m Aalto Ice Tank facility that can operate with water depths as high as 2.8 m; refer to Kim et al. (2015) for a detailed description of the experimental setup. A system of ropes was used to tow an approximately 1000 kg ice block into a purpose-built target at speeds of 1.0 and 2.0 m/s (Figure 1). The transverse motion of the ice block was controlled by steering ropes to ensure a direct impact on the target.

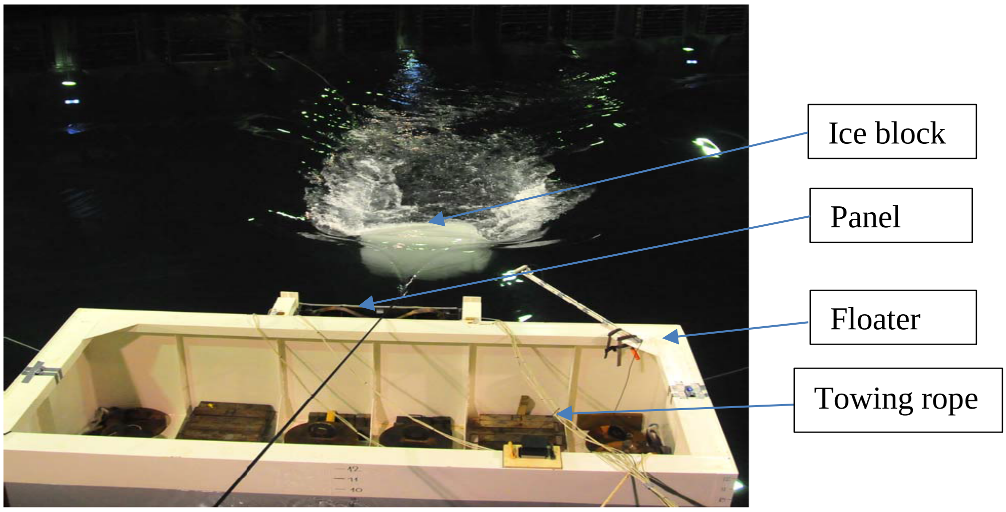
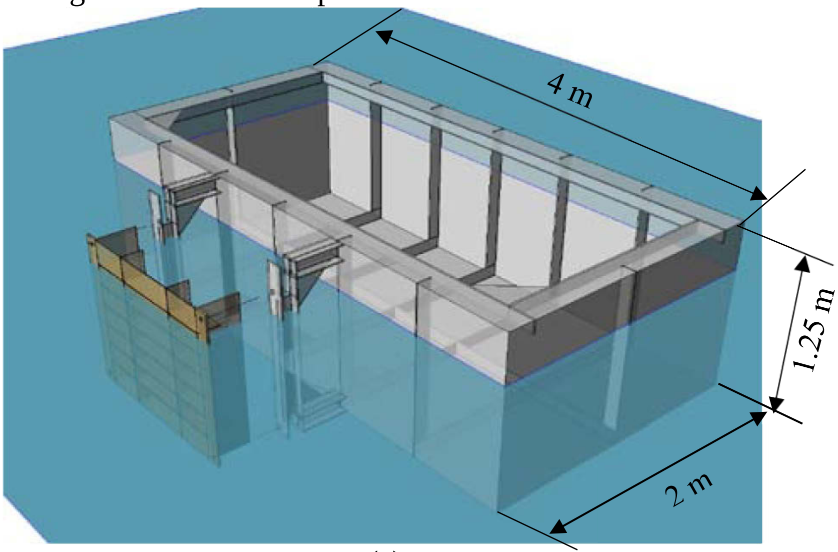
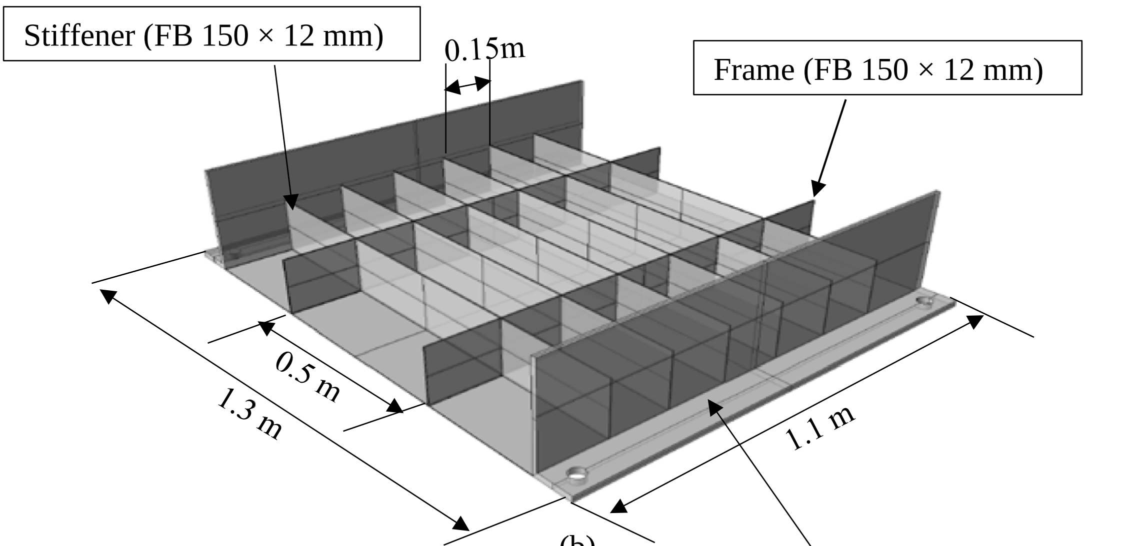


Figure 1. Photo of impact event from one of the tests.



(a)



(b)

(c)

Figure 2. Geometry of the impacted structure and ice block: a- attachment scheme of a stiffened panel with the floater; b- stiffened panel; c-ice block.

Figure 2 shows the geometry of the impacted structure and the ice block. The impacted structure consisted of a stiffened panel bolted to a floater. The global dimensions of the floater at the water plane were 2 m × 4 m, with a draught of 0.95 m and a total height of 1.25 m. The total weight of the floater including the 12-mm thick impact panel was 7537 kg. The ice blocks were manufactured in molds with in-plane dimensions of 1.0 m × 1.2 m and a height of 0.9 m. Finally, they were cut into the test shape, as shown in Figure 2 (c).

The overall dimensions of the panel were 1.1 m × 1.3 m. The panel was supported by six transverse flat-bar stiffeners with a height of 150 mm and a spacing of 500 mm, as shown in Figure 2. The total plate area of 1100 × 1100 mm^2 (excluding the L-profiles) was wider than the expected ice crushing area. A total of 18 impact tests were conducted in water. Test no. 11 was selected as the analysis object because it most closely represents a central impact. In this case, the ice block with a weight of 850 kg impacted the floater with a speed of approximately 2 m/s.

SIMULATION SETUP AND RESULTS

This section presents the technique, computational details and results from numerical simulations for one particular test. The modeling techniques used by Gagnon and Derradji-Aouat (2006) are applied here, with minor changes. The modeled region of the water and air, including the floater and spherical ice block, is shown in Figure 3. The length × width × depth dimensions of the region were 12 × 10 × 4 m, where the top 1.5 m was air. The dimensions of the floater were the same as in the test. For simplicity, the ice block was assumed as a sphere with radius R = 0.61 m. The water, ice block and air were meshed using 8 node solid elements, and the floater using 4 node Belyscho-Tsay shell elements with 5 integration points through the thickness.

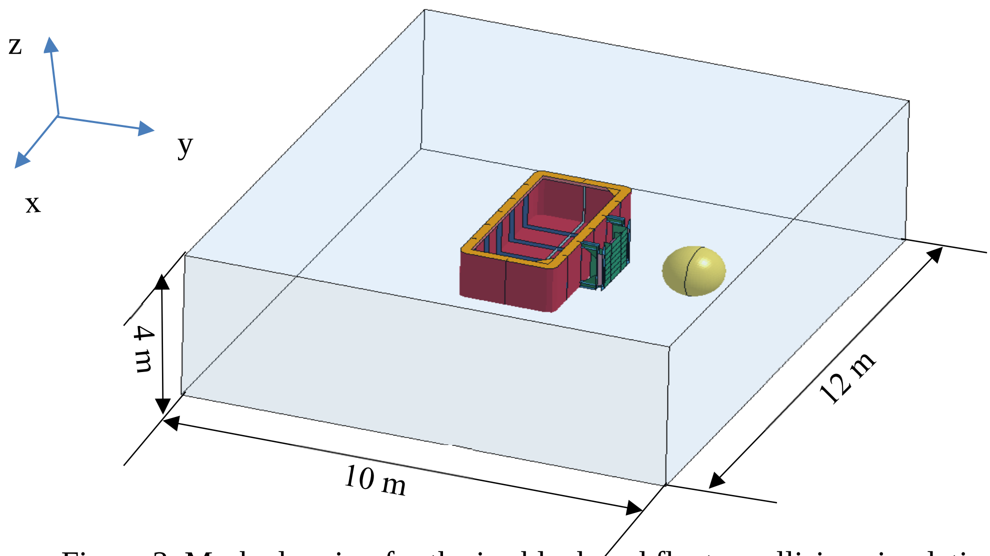


Figure 3. Meshed region for the ice block and floater collision simulations.

LS-DYNA contains a large suite of material types that can be applied to objects within the simulation. The use of rigid bodies rather than deformable components can significantly speed up the calculation by skipping the process of checking and updating the status of every single element at each time step. In Test no. 11, the structure was sufficiently strong to crush the ice with no permanent deformation of the impacted plate. Hence, for the present simulation, the floater was treated as a rigid body, which could make its simulation run quickly. Similarly, the back half of the ice mass was meshed with rigid brick elements because it was relatively far from the impact area. The remaining part used the material model and input parameters proposed by Liu et al. (2011a), including an elliptic yield criterion and a strain-based pressure-dependent failure criterion for freshwater granular ice. The following parameters were adopted: initial failure strain 0.008, density 900 kg/m^3, Poisson's ratio 0.3, elastic modulus 9.5 GPa, cut-off pressure for the tensile strength -2 MPa, and yield surface constants a_0 2.588 MPa^2, a_1 8.63 MPa, and a_2 -0.163.

To improve the calculation efficiency, the front of the ice block was given rigid body properties for the initial stage of the simulation. Before the actual collision occurs, it is necessary for the ice to be activated, that is, its properties need to be changed to realistic values. The switch can be performed automatically through the use of the command "DEFORMABLE_TO_RIGID_AUTOMATIC".

To avoid numerical instability, at the start of the simulation, the value of velocity was input as increasing from 0.0 m/s to 2 m/s (rather than applying a constant value of 2 m/s at the start of the simulation) (Derradji-Aouat and Earle, 2003). As shown in Figure 9, once at the velocity reached 2 m/s, it was kept constant throughout the rest of the simulation. However, just before the impact, the velocity term was released, and the ice was allowed to continue its forward movement. This was achieved through the use of the command "BOUNDARY_PRESCRIBED_MOTION_RIGID".

There are practical limitations to the smallness of the size of the elements used in a simulation because the time step is determined by the size of the smallest element in the mesh. Furthermore, if all the elements are small, then there are a huge number of them that are involved in the computations. Either or both these factors can lead to extremely long run times. However, it is necessary to utilize fine-mesh components of the ice block and the panel to enable proper interaction. Day (2010) states the mesh should be as uniform as possible, with elements of roughly the same dimensions in the region where coupling takes place. Considering these factors, the element size used in the simulation is given in Table 1.

Table 1. All parts details.

Part	Element type	Element size	Material model	Number of elements
Air	*SECTION_SOLID	100 mm	*MAT_NULL	170882
Water	*SECTION_SOLID	100 mm	*MAT_NULL	284804
Floater	*SECTION_SHELL	100 mm	*MAT_RIGID	3420
Panel	*SECTION_SHELL	50 mm	*MAT_RIGID	253
Back half of ice	*SECTION_SOLID	40 mm	*MAT_RIGID	41200
Front half of ice	*SECTION_SOLID	40 mm	*MAT_USER_DEFINE_ MATERIAL	35360

A suitable distance (1 m) was set for the ice block to travel to develop a head wave before the collision while avoiding an overly long volume of water that would necessarily slow down the simulation. To ensure that the water and the objects in it behaved correctly during simulations, gravity was applied to the mesh elements by giving a constant acceleration to all parts in the model. This allows a proper hydrostatic pressure gradient to develop in the water early in the simulation, enabling the formation of free surface waves.

In LS-DYNA, two objects with different materials can overlap with each other within some volume of the mesh and introduce errors into the simulation. Hence, it is necessary to ensure that the water is removed from the volume that is to be occupied by the object when the ice block model and the floater model are inserted in the LS-DYNA k-file. This is done for shell objects and spherical shapes within LS-DYNA, using the command “INITIAL VOLUME FRACTION GEOMETRY”.

The water and air were modeled with ALE hexahedrons, and the floater and ice block were modeled with Lagrangian shells and solids, respectively. In the model, the Lagrangian mesh did not share nodes with the ALE mesh. Rather, the two meshes interacted via a coupling algorithm defined by the command “CONSTRAINED_LAGRANGE_IN_SOLID”.

The contact algorithm must take into account the emerging surface that results from the eroded elements. Thus, the “ERODING_SURFACE_TO_SURFACE” contact method with SOFT option 2 (Hallquist, 2007) was used to define the contact between the ice block and the panel.

Verification of fluid modelling

To verify the fluid modelling in LS-DYNA, analyses were performed to calculate the added mass coefficients of the floater and the ice block. The coefficients were compared with the frequency-dependent added masses calculated by WADAM based on potential theory.

In LS-DYNA, the simulations of the floater oscillated by applying a harmonic force history in the y-direction (sway), considering that sway was the predominant motion during the collision. Using the time history for the floater acceleration and displacement, added mass coefficients for the floater in sway were calculated for a range of frequencies between 12 and

50 rad/s, considered representative of the impact. The added mass coefficients were found using the following procedure.

The time instant for maximum displacement is found. At this time, the velocity of the floater will be zero, and the only contribution from the floater will be inertial forces, Eq. 1.

$$(M + A_{22})\ddot{y} = F(t) \qquad (1)$$

Here, M is the mass of the floater, A_{22} is the added mass in sway and F (t) is the harmonic force. $\ddot{y}$ is the acceleration of the floater.

The added mass coefficient was found by solving Eq. 1 with respect to A_{22}. The values were made dimensionless by dividing the added mass by the real mass of the floater at the given draft. The same method was used for the ice block. The results from LS-DYNA are plotted together with the added mass coefficient values from the WADAM analysis in Figure 4 and Figure 5.

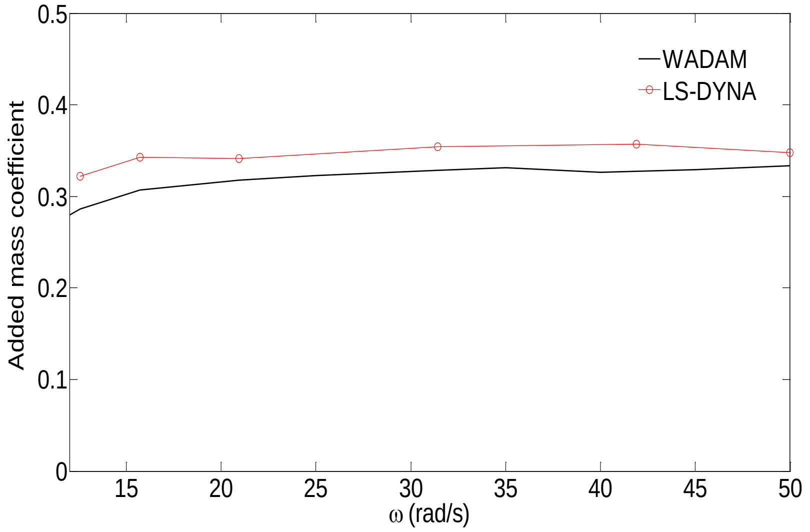


Figure 4. Comparison of added mass coefficients from LS-DYNA and WADAM for the floater (ω is the frequency).

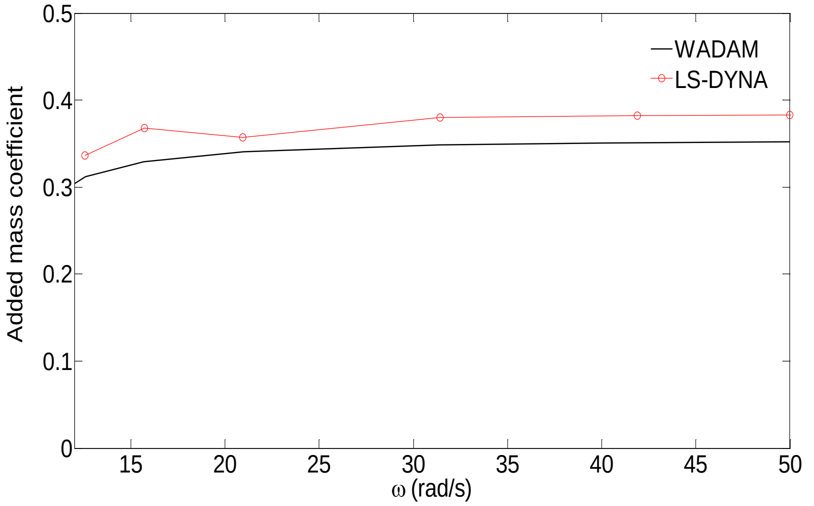


Figure 5. Comparison of added mass coefficients from LS-DYNA and WADAM for the spherical ice block (ω is the frequency).

It is observed that the added mass values calculated using LS-DYNA are very close to the values calculated in WADAM for high frequencies (ω ≥ 10 rad/s). It is therefore concluded that a collision analysis using FSI may give realistic results.

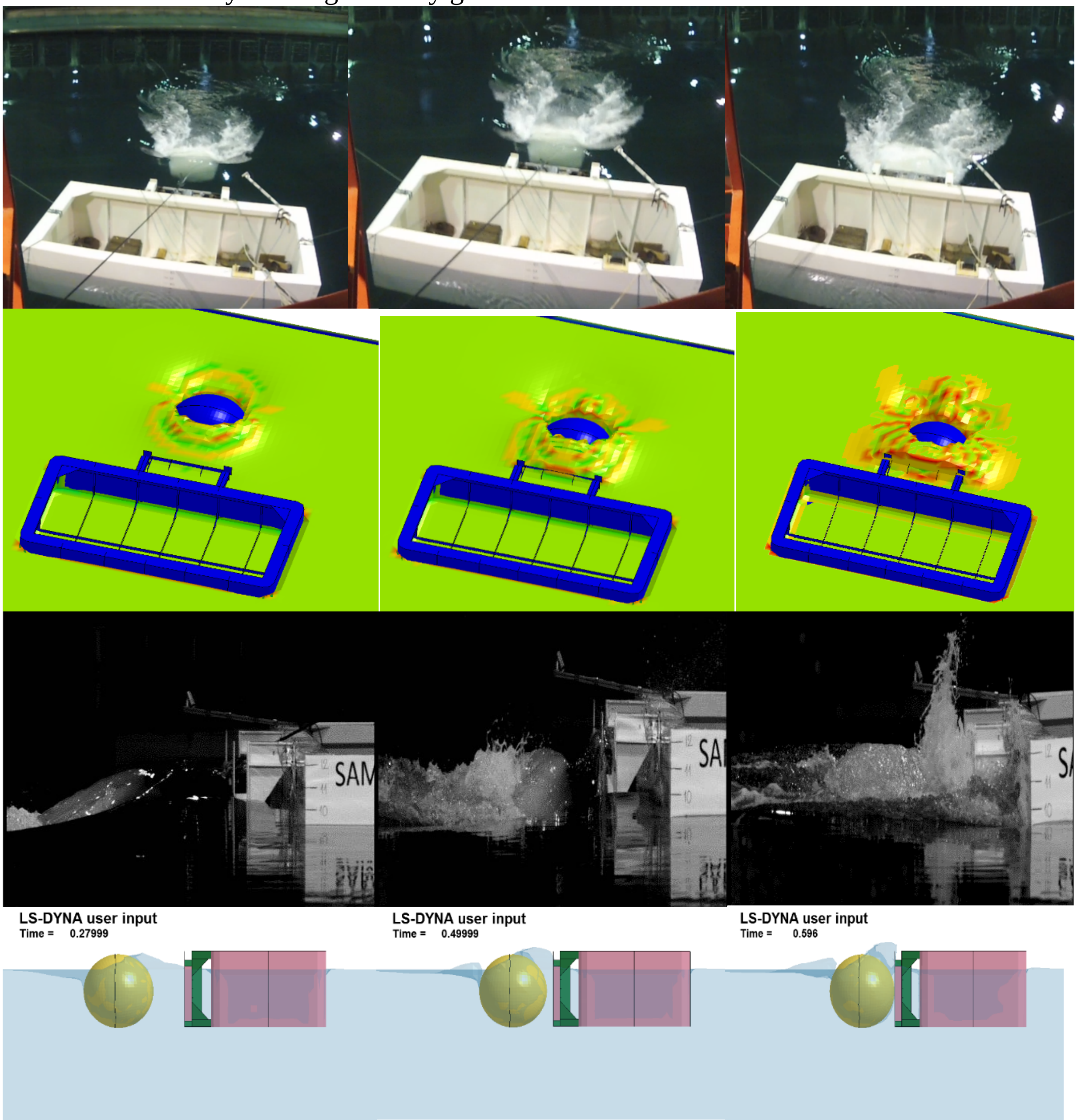


Figure 6. Sequence of images from test and simulation.

Verification of FSI technique for analysis of an ice-structure collision

To verify the FSI technique for the analysis of an ice-structure collision considering the surrounding seawater, the results of laboratory experiments were used. Figure 6 shows a sequence of images from the test and the simulation. The ice block generated a progressive disturbance (a bow wave) that caused a water pile-up in front of the panel before the actual impact. Similar results could be observed in the high-speed video (HSV) of the test. The floater exhibited a lateral response to the bow wave in the simulation. A very slow drift of the floater in the direction of the impact before the actual impact can be observed in Figure 9. The high speed video registered the same effect. This drift is caused by the water pile-up (see Figure 6). Figure 7 shows a comparison between the acceleration of the floater obtained by simulation and that measured in the test. It is noted that the acceleration and velocity are in the direction of the impact and the force is normal to the floater's side surface in Figure 7, 9 and 8. It can be seen that a good agreement between the simulation and test was obtained, where the maximum sway acceleration of the floater for the simulation and for the test were 22.2 m/s^2 and 21.0 m/s^2, respectively.

Table 2. Summary of test results.

Test no.	Maximum panel deflection (mm)	Peak load (kN)	Velocity before impact (m/s)	Common velocity after impact (m/s)	Maximum sway acceleration (floater) (m/s^2)
11	0	222	1.8[a] (0.1[b])	0.2[c] (0.3[d])	21.0

[a] Average ice block velocity from high speed video records.
[b] Average velocity of the floater estimated from high speed video records.
[c] Velocity of the floater after the impact, as estimated from high speed video.
[d] Common velocity predicted by collision mechanics.

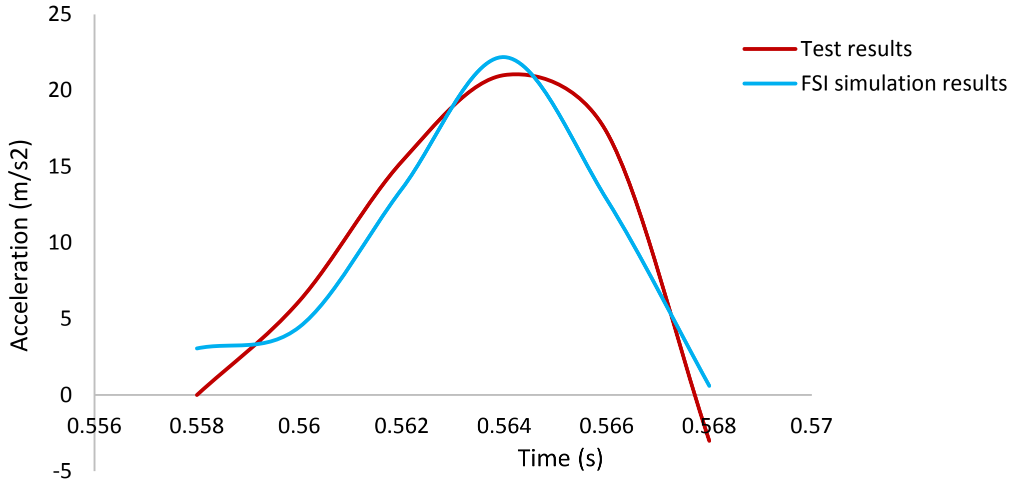


Figure 7. Acceleration of the floater versus time during the collision.

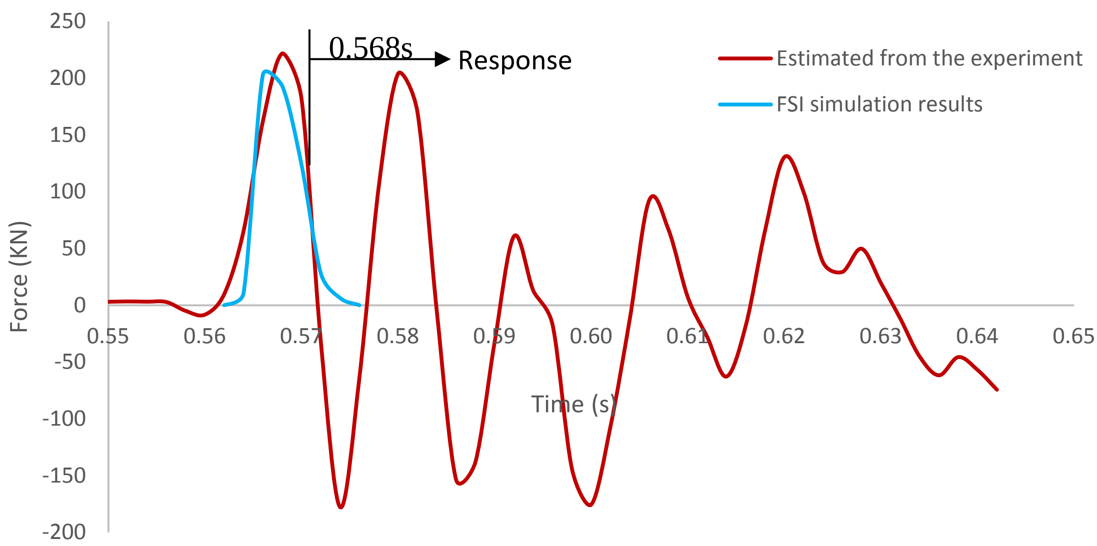


Figure 8. Impact force versus time; note that in the experiment, the impact force history was estimated from the measured sway acceleration of the floater as Eq. 1, where the added mass A_{22} was assumed as 0.4.

Figure 8 shows the force estimated using the acceleration data from the experiment and the force obtained by the simulation. The simulated peak force was approximately 203 kN, compared to the 222 kN in the experiment. Using Figure 4, we determined that the added mass coefficient of the floater during the impact is approximately equal to 0.32 in the simulation. For comparison, an added mass coefficient of 0.4 is the most frequently used in the traditional approach to collisions between two ships (Minorsky, 1959). In general, the added mass coefficients will depend both on the duration of the collision and on the relation between the collision force and the deformation (Motora et al., 1971). This may explain the difference between the added mass coefficients calculated from the simulation and the added mass coefficients assumed by the traditional approach. After approximately 0.568 seconds (see Figure 8), the oscillating force estimated from the experiment is due to the impact dynamic response of the steel floater. However, a rigid material was used for the floater in the simulation, which caused a different trend in the force history compared with that in the experiment. Overall, the force history of the first impact event compares reasonably well with the experimental results.

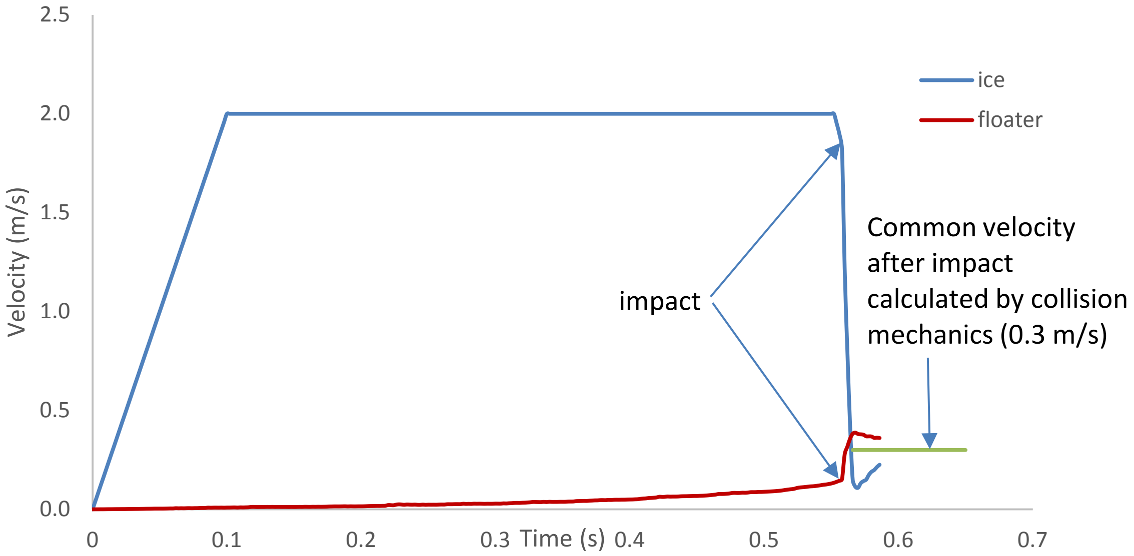


Figure 9. Velocity of the ice and floater versus time.

The velocity history of the ice block and the floater are plotted in Figure 9. The velocity of the ice block and the floater before the impact were 1.82 m/s and 0.15 m/s, respectively, which are close to the experimental values in Table 2. After the impact, both the ice and the floater moved in the direction of the impact in the simulation. This phenomenon could also be observed in the test. It should be noted that the velocity of the ice increases for a short time after the collision because of hydrodynamic effects from the surrounding water.

These differences between the test results in Table 2 (velocity from HSV) and the numerical simulation are not surprising because the velocity in the tests is the average velocity, which was estimated using only a few images extracted from the high-speed video recordings after the impact. The common velocity of the ice block and the floater after the collision is 0.35 m/s, which is close to that predicted by collision mechanics (i.e., 0.3 m/s).

CONCLUSION

The simulation using the FSI technique produced reasonable values for the acceleration/load time history obtained in the actual ice collision experiments. There is a good agreement between the simulated first impact event and the experimental data. The simulation data roughly approximated the maximum sway acceleration and peak force. The hydrodynamic effects from the surrounding water should be considered because they will affect the motions of the ice and floater and the impact force during the collision. The acceptable compatibility of the simulation and experimental results proves that the FSI technique can be applied to the analysis of ship-ice collisions.

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