Ice-Steel Impact In Arctic Operations

STePS² Project Tests Ice Load Pressures for Arctic Vessels

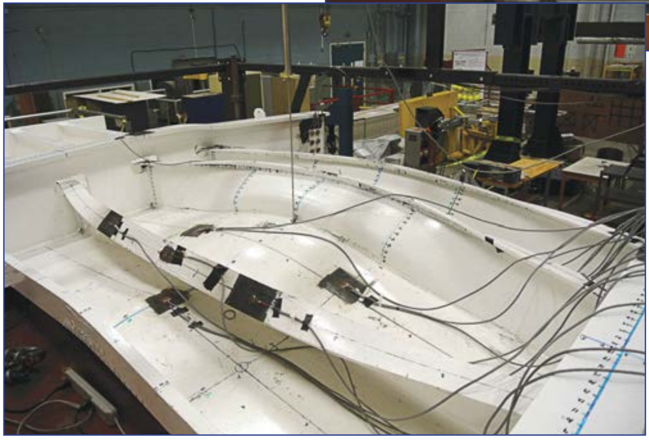
By Dr. Claude Daley • Dr. Bruce Colbourne • Andrew Safer

Increased interest in oil and gas exploration, and shipping in the Arctic has highlighted the need to better understand impact forces between ice and steel structures, and to improve the tools that are used to design ships and offshore structures for year-round Arctic operations.

Sustainable Technology for Polar Ships and Structures (STePS²) at the Faculty of Engineering and Applied Science at Memorial University in St. John's, Newfoundland, Canada, is a five-year project focused on these objectives. Currently in its fourth year, the STePS² team has conducted hydrodynamic ice-ship hull interaction tests and a range of static and dynamic experiments that collide 1-meter-diameter ice cones with steel structures at speeds up to 6 meters per second.

Typical ships in the Arctic sail at 4 to 6 knots (2 to 3 meters per second), whereas a ship accidentally striking an iceberg off the east coast typically sails at 12 to 16 knots (6 to 8 meters per second). To date, experiments have involved the use of two stationary steel frames and a small (1/4-scale) double-pendulum apparatus (1-meter-cube structure).

A large double-pendulum apparatus (4 by 4 meters) is in the final stages of construction and will provide near full-scale ice-impact scenarios. Experiments scheduled to begin in April will be the first laboratory tests of ice and steel-structure collisions at full-scale Arctic speeds.



(Top) Large structural panel after experiencing 2.7 meganewtons of ice load (side view). (Photo Credit: Claude Daley)

(Bottom) Large structural panel after experiencing 2.7 meganewtons of ice load (top view). (Photo Credit: Claude Daley)

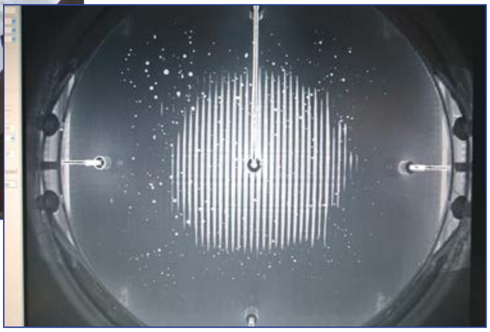
Pressure Testing

In offshore areas where historical ice data are available, in order for oil and gas operators to predict outcomes, a better understanding of the conditions and elements that influence ice loads is required. Variables include the type of ice, its shape, temperature, grain size, the speed of interaction, and the shape and surface condition of the object with which it collides. For the past 25 years, the consensus among researchers has been that ice pressure follows a standard pressure-area curve: If you know the area, you will know the pressure and will be able to calculate a load.

The STePS² experiments have shown that this is often not the case because the load changes with subtle changes in shape, structural stiffness and impact velocity. One finding, for example, is that pressures are very high at very slow speeds, contrary to the notion that an impact occurring at a high speed creates a larger load.

Static Tests. In November, an experiment was performed to test the overload capacity of the side shell of a ship's hull (design load: 220 kilonewtons), which was held in place by a steel support frame. An ice cone was slowly pushed against the ice-class ship structural panel, at the rate of 1 millimeter per second, to a maximum load of 2.7 meganewtons—more than 10 times the design load—and nearly the limit of the hydraulic ram.

The panel was deformed into the shape of the cone pushing against it, which had slowly flattened from its original



(Left) Small double-pendulum apparatus just after impact between ice cone and plate. (Photo Credit: Claude Daley)

(Right) Ice pressure strips in high-resolution ice impact module. (Photo Credit: Claude Daley)

pointed tip, but there were no tears or through-thickness cracks in the steel, contrary to expectations. During the early stage of the loading, a crack appeared in one of the welds that joined one section of the frame to another, but as the deformation increased with additional pressure, the crack closed.

This experiment demonstrated that at slow loading rates, ice exhibits creep plasticity—increased ductility at low strain rates—and can, in effect, heal itself while being deformed. Due to the stroke limitations of the hydraulic ram, what is still unknown is the maximum load the hull could have withstood before tearing.

This test indicates that marine steel structures can sustain loads far in excess of their design point when ice is pushed against them at extremely low speeds. This would occur if, for example, a vessel is trapped under pressure in a moving ice field, or ice pushes against a fixed or moored stationary offshore structure at a very low speed. If a real ship were to sustain similar damage, it would be able to reach its home port, and repair costs would be modest. If, instead, a tear occurred, the loss would be orders of magnitude greater—as both lives and the environment would be at risk.

This experiment, and other static tests conducted for STePS^2, have contributed to an improved understanding of the overload capacity of steel structures under ice loads. Before these tests, it was believed that there was a pressing need to devise new ways to lay out a ship's structure in order to prevent fracture. Based on the test results, it appears that the current methods are adequate, recognizing that there is always room for improvement.

This experiment also suggests that a collision-resistant steel structure could be made from lighter material. Dents, such as the one that was produced in the lab in which the vessel remained watertight, may be deemed to be acceptable in extreme circumstances. This could result in considerable savings in up-front capital costs.

Dynamic Tests. Dynamic ice-impact tests have been conducted using a small (1/4-scale) double-pendulum apparatus comprising two 100-kilogram pendulums that are set to collide, with a 0.25-meter ice sample attached to one of them.

Tests have been conducted at forces up to 50 kilonewtons and at speeds up to 3 knots. Tests at 1.5 meters per second demonstrated that the stiffness of the structure influences the load experience, just as a load striking a hard spring produces a higher load than one striking a soft spring. A 1/4-inch plate did bend, whereas a 3/4-inch plate did not bend but experienced a much higher load.

Another finding was that flat-on-flat contact between the ice and the steel plate (similar to a ship slamming into a wave) combined with high speeds produces shock conditions that cause very high loads on the structure and, at the same time, shattering inside the ice due to massive inertial effects. When two objects traveling at different speeds collide, the slower-moving object is forced to accelerate at near-infinite speed so that they are moving at

(Left) Large double-pendulum apparatus. (Photo Credit: Claude Daley)

(Right) 3D computer-aided design image of the moving ice-load apparatus. (Credit: Bruce Quinton)

the same speed at the point of contact. The mechanical information is transmitted through stress waves. It is unknown whether this type of shock occurs on real ships. If this is found to be the case, progressive, sustained, incremental damage to the hull would result, with the ship plates gradually bending inward with each successive impact. Coatings that prevent corrosion would also be affected. If this is found to occur in ships, the steel could be designed to withstand the shock impact.

To measure the impact forces and pressure distribution within the ice in the large (4-meter-tall) double-pendulum experiments, STePS^2 researchers will use an impact module comprising a high-spatial-resolution array of pressure sensors covered by a thin metal sheet, against which the force will be applied. These sensors will rest on an 18-inch-thick block of clear acrylic with a high-speed camera mounted behind it to capture the pressure information.

The impact module used for both dynamic and static testing was developed by Dr. Robert Gagnon, a physicist at the National Research Council Canada (NRC) in St. John's, located next door to Memorial University's Ocean and Naval Architectural Engineering structures lab, where the STePS^2 experiments are being conducted. The capability to measure internal pressures is key, as pressure zones are not evenly distributed in ice, and they change as the ice fractures and pieces are extruded from the contact area.

Numerical Modeling

Based on their findings, STePS^2 researchers are developing numerical models of ice and its behavior in various scenarios, which are then validated in a high-performance computing environment. LS-DYNA is a dynamic finite element analysis software that is being used to model local impact effects. The models being developed reflect the properties of ice discovered in the experiments.

To numerically model global forces and effects on a ship transiting ice, instead of using standard continuum mechanics, the STePS^2 approach is to model via event mechanics using parallel graphical processing unit computing. This method processes algorithms 90 times faster than a normal computer.

Future Dynamic Tests

As ice moves along a ship's hull, contact typically occurs at a glancing angle, indicating that the way a moving load is transferred along the structure could enhance tearing risk. To address this, Bruce Quinton, a graduate student in the STePS^2 team, is building an apparatus to test moving loads. A rail system connects the yellow strongback, while the aluminum piece is the structural holder support for the panel. This will be the last major physical experiment conducted for STePS^2. At 1/4 scale of the ship structural panel test—thousands to tens of thousands of pounds—this test will take place in a cold room.

While this issue has been studied numerically, this will be the first physical experiment to measure plastic damage from moving ice loads. According to current knowledge, as the ship digs into the ice, plasticity in the steel structure piles up, increasing the possibility of tearing open the structure. An improved understanding of these dynamics should inform the process of assessing the safe speed for ships.

Conclusions

The STePS^2 project was initiated to improve the understanding of ice actions on Arctic ships and structures. The work to date has cast new light on many aspects of ice loads, structural response, and viable design and assessment strategies. It has become clear that ice-structure interaction includes many elements that interact. The simple ice-engineering load descriptions developed in the 1980s are becoming obsolete.

When the project concludes in June 2014, the new findings will be incorporated into design tools and methods that will enable engineers to design ships and offshore structures with increased accuracy.

A large number of new issues have arisen in the course of the work. The next steps beyond STePS^2 point to much more realistic numerical modeling, larger-scale laboratory investigations and comprehensive full-scale studies.

Acknowledgments

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The National Research Council Canada is a key research partner. A total of 51 graduate and work-term students are conducting research over the life of the project. ■

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Dr. Bruce Colbourne is a STePS^2 co-investigator and project manager. He is a professor and researcher specializing in predicting loads from ice and waves on ships and offshore structures. He also works with the Canadian Standards Association's committee for offshore structures standards. Colbourne is a graduate of Memorial University of Newfoundland (MUN) and the Massachusetts Institute of Technology, and holds a Ph.D. in Ocean Engineering from MUN.

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