POAC'25
St. John's, Newfoundland and Labrador, Canada

Proceedings of the 28th International Conference on Port and Ocean Engineering under Arctic Conditions
Jul 13-17, 2025
St. John's, Newfoundland and Labrador Canada

Rapid High-capacity Impact Test Apparatus (RHITA) for Conducting Ice and Model / Full Scale Structure Interactions

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ABSTRACT

The Rapid High-capacity Impact Test Apparatus (RHITA) was developed specifically to simulate at full scale (or near full scale) loads imparted and responses generated when a free-floating iceberg keel contacts a pipe, flowline or cable laid on the seabed at representative interaction speeds. This scenario is of interest as risk analyses have shown that the majority of iceberg interaction events on the Grand Banks will be from free-floating icebergs, with scouring iceberg interactions constituting less than 10% of events (King, 2019). The design, fabrication, assembly and commissioning of RHITA is documented. Tests conducted to date are described, with a high-level overview of observations, results and lessons learned. The incorporation of RHITA results into iceberg subsea risk modelling is also discussed.

KEY WORDS: Ice; Crushing; Testing, Subsea; Pipeline, Flowline, Cable.

INTRODUCTION

Subsea infrastructure in the form of pipelines and flowlines have been used on the Grand Banks to support hydrocarbon production and are becoming more common as tiebacks are used to extend and enhance production. The development of offshore wind power will require cables to collect and export power generated using turbines. While trenching can be used to protect this infrastructure from interactions with the keels of icebergs which drift into the region, the preferred option is to lay pipes, flowlines and cables (hereafter collectively referred to as "lines") directly on the seabed. While considerable effort has gone into physical and numerical modelling of iceberg scouring and incorporation of resulting models into a probabilistic risk analysis framework for burial of trenched pipelines (Phillips et al., 2005; Phillips et al., 2012; King et al., 2009), the development of a similar framework for direct contact between icebergs and lines laid on the seabed is a more recent undertaking, which has been advanced through programs such as AFT (Alternatives to Flowline Trenching, see i.e. C-CORE, 2020) and SIIBED (Subsea Ice Interaction Barriers to Energy Development, see Ralph et al., 2023).

The SIIBED program was focused around the development of a numerical model for analyzing the response and behavior of lines subject to direct iceberg keel contact (Barrett et al., 2023), which includes the stress and deformation of the line itself, the displacement of the line during the interaction (along and/or into the seabed, see Figure 1), and the transmission of loads along the line to other subsea infrastructure. The major inputs to the development of the numerical model are the physical characteristics of the lines (Ralph et al., 2023), the response of the underlying seabed during the interaction events (Phillips et al., 2023), and the loads that can be imparted on the lines by the iceberg keels. Here, the focus is on a novel test facility (Rapid High-capacity Impact Test Apparatus -RHITA) that was designed, constructed and subsequently used to conduct interaction tests between a large 3.5 metric ton ice sample and various impactor geometries and sample line types.

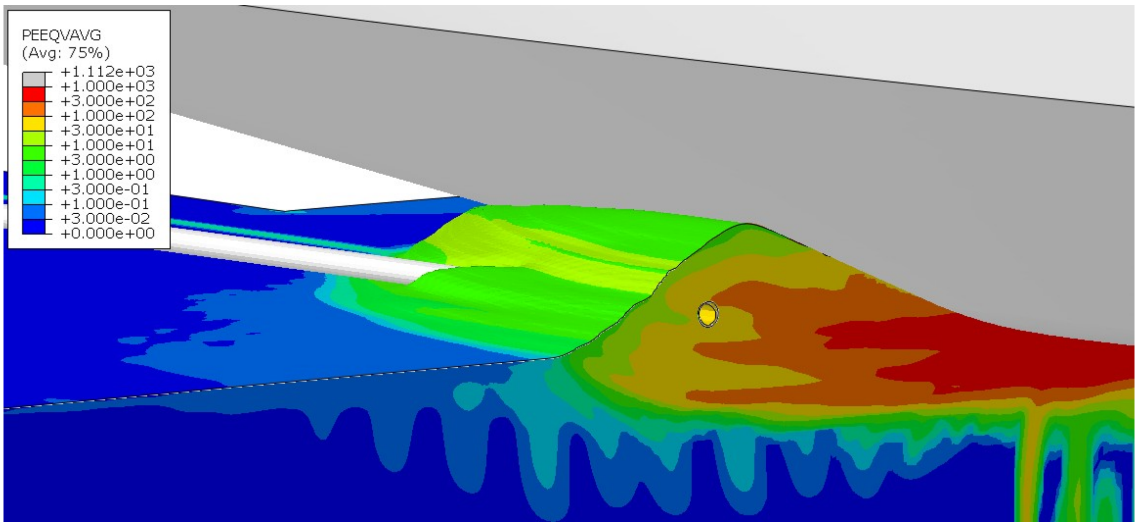

Figure 1. Finite element model of keel interaction with cable on seabed (C-CORE, 2020)

RHITA DESIGN AND CONSTRUCTION

The need for and an initial design concept for a device for full-scale testing of ice keel/line interactions was a result of work on marginal field developments (Muise and Ralph, 2018; Bailey and Phillips; 2018). Design and fabrication of RHITA began during AFT (C-CORE, 2020) and concluded during SIIBED (Macneill et al., 2023). Progress was problematic during the COVID epidemic due to supply chain and manpower issues. During design, consideration was given to desired test configurations, adaptability, clear access for recording visual results, ice sample dimensions and apparatus loading magnitudes. The ability to test lab grown or natural ice was also incorporated. The apparatus frame is self-reacting and mechanically rigid (see Figure 2).

FEA and CNC machining facilities were used extensively during design and manufacturing. All design and FEA was carried out by C-CORE. Fabrication was coordinated by C-CORE between 6 machine shops and a welding facility. Design of the hydraulics and controls was carried out by two external contractors specializing in these fields. Final assembly, hydraulics tuning and testing was a joint effort by C-CORE personnel and external experts. Maximum design loads were selected to be 2MN horizontally and 4MN vertically. Actuation of the indenter is accomplished with a hydraulic system that powers two rams, each with a piston diameter of 7". An accumulator bank, backed by gas bottles and a nitrogen skid (visible on the right side of Figure 2) supplies the rams with high pressure oil at a flowrate which gives a maximum test velocity of 0.5 m/s.

Figure 2. Completed frame design (Macneill et al., 2023)

The rams are attached to a test carriage which traverses along carriage rails incorporated into the top beams. The indentor assembly is attached to the test carriage and has load cells incorporated between the two components that measure horizontal and vertical loads. The indentor assembly can be configured with rigid steel semicircular indentors, representing lines with diameters of 6, 10 and 12.75 in (152, 254 and 324 mm), or with holders for testing lines of various sizes. The rigid indentors are equipped with tactile pressure sensors to measure ice crushing pressures during testing (Figure 3). Displacement transducers attached to the hydraulic cylinders measures displacements during tests. The maximum stroke length is 2m (80in).

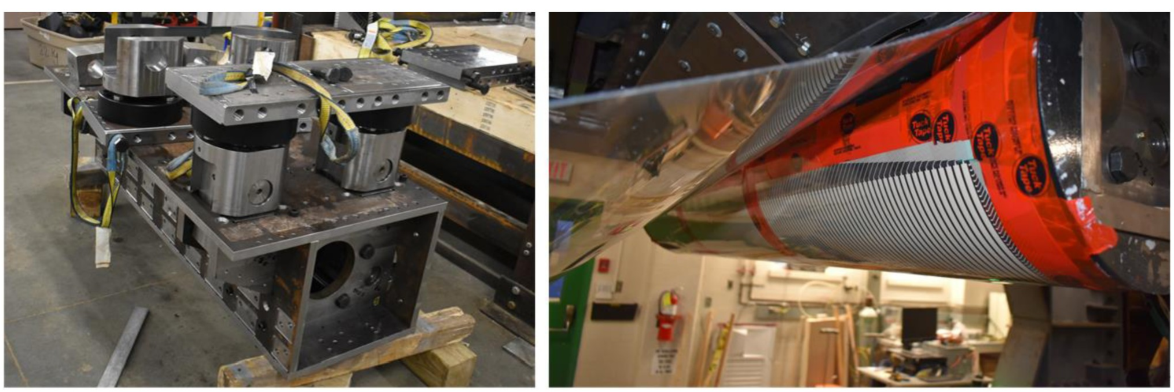

Figure 3. Load cells, left, and tactile pressure sensor, right (Thijssen et al., 2023)

Two molds were designed and constructed for creating ice samples for testing. Ice sample dimensions are 2.5m x 1.5m x 1.0m (Length × Width × Height), which is the maximum size that can be accommodated in C-CORE’s cold room. Ice is grown in the mold a manner that best approximates iceberg ice properties. The top half of the mold is removed prior to testing to expose 0.5 m of ice for interaction with an indentor or line sample. The mold with the ice sample is beyond the lifting capacity of the overhead crane or C-CORE’s forklift, requiring a two-step operation for loading (see Figure 4). Once loaded, mounting brackets and bracing are installed to ensure the mold does not shift during testing.

Figure 4. Installation of ice sample in mold for testing (Macneill et al., 2023)

TEST PROGRAM

Table 1 shows a summary of tests conducted using RHITA. Initially, tests were limited to a maximum of 0.2 m/s interaction speed due to inadequately sized hydraulic hoses being installed by a contractor, but this issue was rectified later in the test program. Most tests used a rectangular ice block, but in some cases the ice block shape was modified by sloping the contact face or the sides. In addition to the rigid indentors, tests were also conducted with rigid pipe samples of varying wall thicknesses, flexible flowline samples and two electrical cables with differing diameters. Peak forces given in Table 1 are the maximum resultants of horizontal and vertical forces. Figure 5 shows time series of horizontal, vertical and resultant loads measured during tests 2, 5 and 9. Figure 7 shows pressures measured using the tactile pressure sensors at peak global load during Test 5 at 5.55 seconds. Figure 7 shows average line loads for Test 5, calculated along the length of the indentor as it is pushed into the ice. Line loads were calculated from the tactile pressure sensor data by averaging pressure data obtained at each time step along the y-direction shown in Figure 7. The global loads measured using load cells and loads calculated using pressure data from the tactile pressure sensors were in good agreement. In addition to force, pressure and displacement measurements, videos of each test were captured from multiple angles. After each test the ice sample was removed from RHITA and cut with a chainsaw to discern details of the crack patterns within the remnants of the ice block.

Tests 14, 19 and 20 were conducted on flexible flowline samples provided by the Pipeline Research Council International (PRCI). Figure 8 shows the flexible flowline mounted in RHITA for testing. No damage was discernable on the flexible flowline after testing; even the HDPE coating was undamaged. Likewise, the Schedule 80 pipe (Test 13) was undamaged. However, the Schedule 40 pipe (Test 16) collapsed during testing (Figure 9). The HVDC electrical cable (Test 15) only showed minor surface abrasion (Figure 9). Testing was not conducted to confirm the functionality of the electrical cable after testing, but should be included in any future investigations of this type.

Also shown in Table 1 are tests using flat plates (Test 18 and 21). These preliminary tests were intended to explore alternative uses of RHITA, in this case as a possible source of data for design of ship's hulls for ice interaction. Details of these tests will be discussed in a future publication. Figure 11 (a) through (d) shows the test setup for a 1” (25.4mm) thick steel plate and ice sample before and after testing.

Table 1. RHITA test summary

Test #	Date (mm/dd/yy)	Pipe Dia. (inches)	Speed (m/s)	Indentation Depth (inches)	Peak Load (kN)	Comments
1	06/02/22	6	0.2	1.5	357	Some pre-existing cracks in ice
2	07/11/22	12.75	0.2	2	932	3 load ramps
3	07/28/22	12.75	0.2	2	386	Gravel embedded, weak layer of ice
4	08/09/22	12.75	0.2	2	621	Gravel embedded
5	30/09/22	12.75	0.2	4	920	3 load ramps
6	04/10/22	12.75	0.2	4	817	Ice sample fully regrown from bottom
7	10/11/22	12.75	0.2	4	545	Truncated sides
8	25/11/22	12.75	0.2	6	692	Deeper indentation
9	12/12/22	12.75	0.2	4	654	Rerun bases case, lower ambient temp.
10	03/01/23	12.75	0.1	4	492	Low speed case and truncated
11	16/01/23	12.75	0.2	4	408	Truncated sides (wide), -5°C ice
12	01/02/23	6	0.2	5	342	Slope on front of ice
13	24/02/23	10	0.2	8	772	10" Schedule 80 pipe, front slope on ice
14	20/03/23	9	0.2	8	798	Flexible flowline
15	06/04/23	4	0.2	4	366	HVDC electrical cable
16	31/05/23	10	0.2	8	1026	10" Schedule 40 pipe, Stepped Front Face, Concave to Match Pipe OD
17	27/06/23	12.75	0.4	6	577	Rigid pipe indenter, Front Face Slope 45°
18	28/09/23	1" Plate	0.3	N.A.	704	Tapered Side Profile, Flat Front Face
19	03/04/24	9	0.2	3	816	3 Core Electrical Cable, Front Face Sloped 45°
20	17/04/24	9	0.5	3	969	3 Core Electrical Cable, Front Face Sloped 45°
21	03/05/24	0.25" Plate	0.3	N.A.	1421	Tapered Side Profile, Rounded Front Face

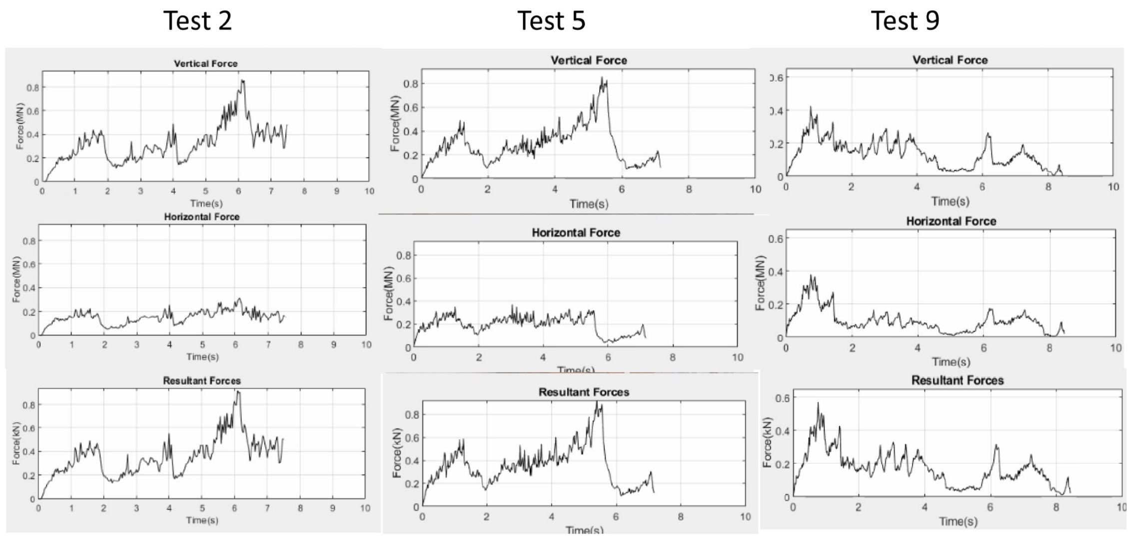

Figure 5. Global loads measured using load cells in Tests 2, 5 and 9 (Thijssen et al., 2023)

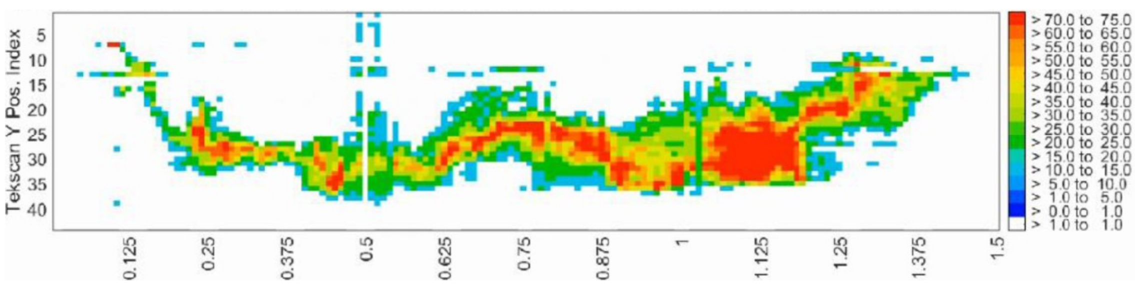

Figure 6. Pressures at peak load during Test 5 at 5.55 seconds (Thijssen et al., 2023)

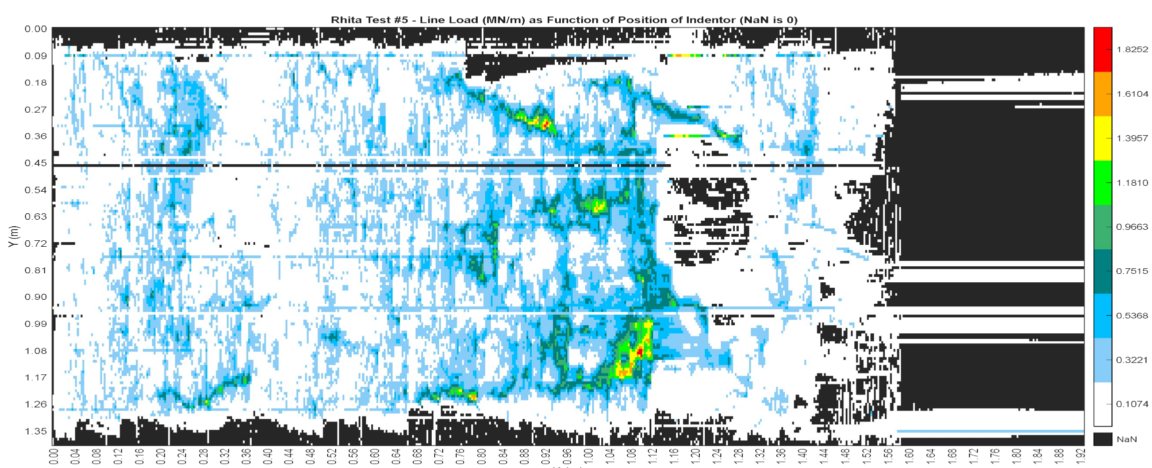

Figure 7. Line loads as a function of indentor position, calculated from pressure data (Test 5)

Figure 8. Flexible flowline, pre-test state (upper image), post-test (lower image).

Figure 9. Schedule 40 pipe, post-test image showing deformed pipe

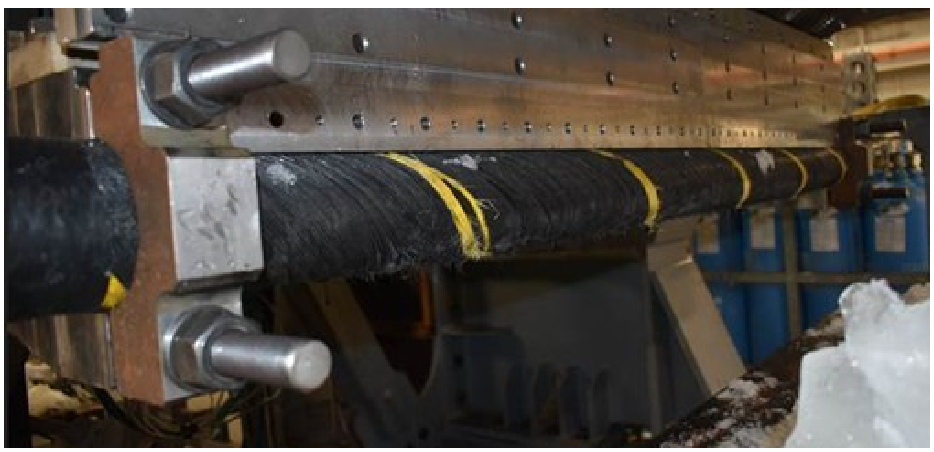

Figure 10. Electrical cable, post-test image (Ralph and King, 2024)

(a) 1" indenter plate mounted to RHITA

(b) Ice sample before final preparation

(c) Ice sample in place for testing

(d) Ice sample after testing

Figure 11. Testing of flat plate

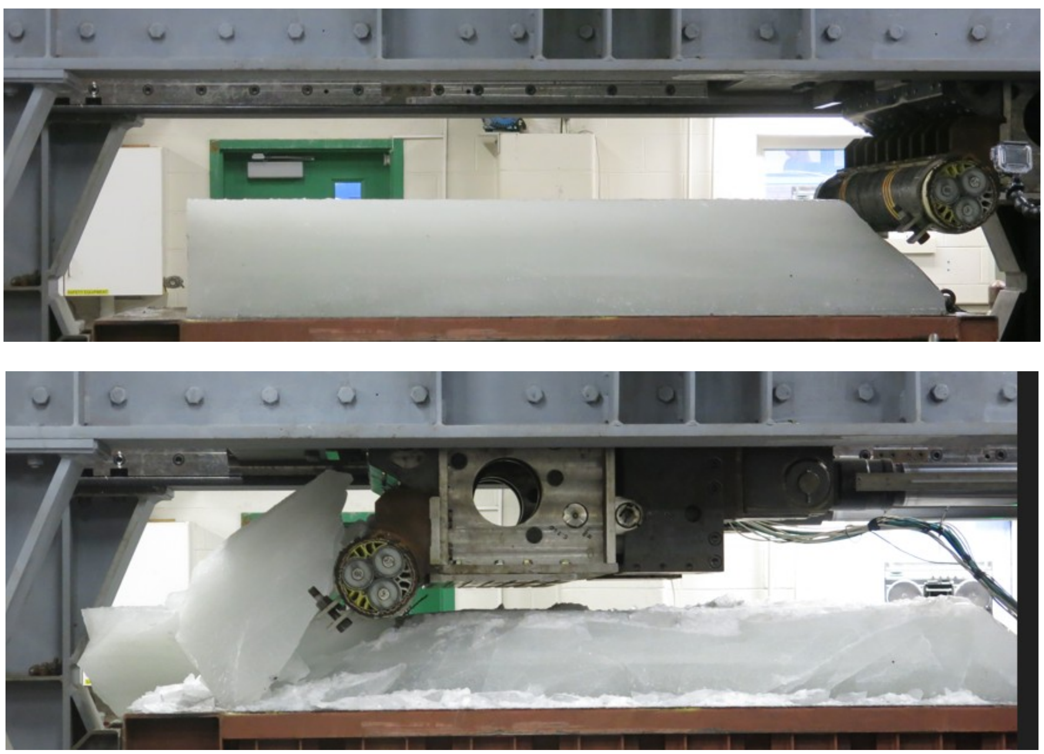

Figure 12. Testing of 3 phase (3 cores) Electrical Cable

UTILIZATION OF RESULTS

The results of RHITA have been used to get first-order estimates of keel ice pressures on a pipe or cable. Fuglem et al. (2023) show how the pressures vary over different contact widths, and examine the influence of different boundary conditions and keel shapes (with and without chamfering). A related objective was to investigate the potential influence of scale on these ice pressures; i.e. could the pressures be significantly different for an actual keel, for which case the extent of ice is larger and the shape and boundary conditions are different than for the RHITA tests. Two numerical approaches were investigated to achieve this. In the first, the cohesive zone was applied (Fuglem et al., 2023, Gribanov et al., 2023). While the method was promising, it was limited in regards to the size of grains that could be considered and computation speed. With the second approach, the Material Point Method (MPM), significant improvements were achieved (Gribanov et al. 2024). Continued development of the MPM approach is recommended. More comprehensive analyses of the test results and comparisons with MPM modelling is planned.

From an FEA perspective, incorporating ice failure limits into ice/line/soil numerical model not only limits the compressive forces generated on the line but also limits the ability of the ice to drag the line.

As shown in figure 13, the electrical cable, in this case, penetrates the reference surface of the ice feature as well as the relatively competent soil.

In comparison to the rigid ice assumption, a reduction in line displacement and tension developed was observed.

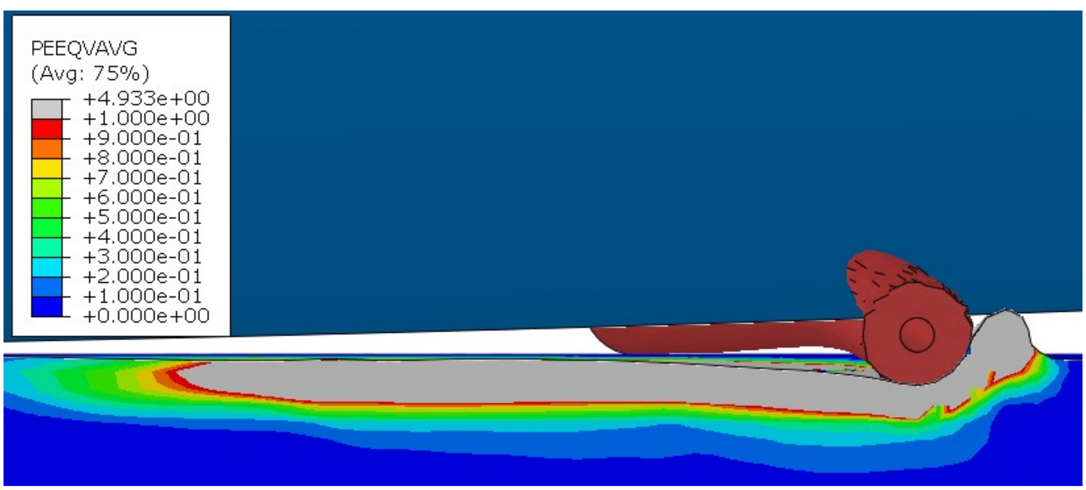

Figure 13. Result of incorporating ice failure limits into numerical model.

From a purely mechanical viewpoint, the results to date also indicate that the test apparatus performs as designed, realizing load magnitudes estimated for planned test types.

CONCLUSIONS

This paper describes an overview of the purpose of the RHITA test facility, its design and fabrication and testing highlights to date. As of 2025, RHITA is fully functional and available for testing. Because of the flexibility incorporated into the testing area and indenter mounting structures, many different types of tests are anticipated in the future.

Conducting the design and fabrication effort of this test apparatus also resulted a furthering of design and manufacturing methods that are useful for other large scale mechanical testing facilities, such as Memorial University's Faculty of Engineering Harsh Environment Research Facility (HERF). Mechanical elements developed for RHITA are being incorporated into various aspects of HERF test facility designs.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of the SIIBED program by the Government of Newfoundland and Labrador via the Oil and Gas Industry Recovery Assistance (OGIRA) Fund. PRCI and Growler Energy are also gratefully acknowledged for providing samples of flexible flowlines and electrical cable samples respectively.

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