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Improving the accuracy of ice load measurement systems

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ABSTRACT

One of the most commonly used methods to measure ice loads on ships has been instrumenting the side shell framing with shear strain gauges. It is a straightforward and robust measurement method and can measure the load magnitude accurately over a wide range of load locations, while requiring only one measurement channel per instrumented frame when using gauges in a Wheatstone bridge configuration. However, recent studies have shown that frame rotation has a significant impact on the measurement accuracy, because in a typical setup, the strain gauges are positioned on one side of the frame. For such a setup, the sensitivity of the instrumentation depends on which side of the frame the load is positioned, which can lead to a significant error in the measured load magnitude.

In this paper, a method to correct this error is studied using the finite element method and laboratory experiments with semi-scale structure. The proposed gauge setup retains the cost-efficiency of requiring only a single measurement channel per instrumented frame, while removing the error caused by the frame rotation. Both finite element method and laboratory results demonstrate that the proposed setup removes the error caused by the frame rotation and can measure the ice load more accurately than the currently used setups when the load is offset to either side of the instrumented frame. The proposed gauge setup has been used in instrumenting icebreaking cruise vessel Le Commandant Charcot in the spring of 2024 and lessons learned from this installation are also presented.

KEY WORDS: Ice load measurement system, Strain gauge, Wheatstone bridge, Finite element method, Semi-scale experiment

INTRODUCTION

Accurate knowledge of design ice loads is important for designing ice-going vessels to be both safe and as efficient as possible. As ice conditions are changing due to global warming, and as the Energy Efficiency Design Index (EEDI) regulations and the strive for better hydrodynamic efficiency has led to the development of new, radical bow shapes, as well as development of new, novel vessel concepts such as the oblique icebreaker (Adams, 2018), there is need to measure the actual ice loads to verify the calculated ice loads. Moreover, ice load measurements allow for the development of more accurate calculation methodologies for ice loads by providing additional insight into the nature of ice loads, and further development of the ice class rules (Traficom, 2021) (IACS, 2019).

The other, more recently emerging application for ice load measurements is the installation of ice load monitoring displays on bridges of ice-going ships to provide guidance for the Master and the crew to aid in safe navigation and to provide support for decision-making.

There are several methods for measuring ice loads, including uniaxial strain gauges installed to shell plating (Adams, 2018), shear strain gauges installed on frames (Adams, 2018) (Piercey, et al., 2016) (Suominen, et al., 2017) and primary support structures (Adams, 2018), compression-tension gauges installed on shell frame webs (ABS, 2021) or uniaxial strain gauges on shell frame flanges to measure frame bending.

The most widely applied method for ice load measurements has been to use two shear strain sensors on a frame. As proven by numerous measurement campaigns and calibration tests with either Finite Element Analysis (FEM) or test pulls, this method is accurate when the load is centered on the instrumented frame. On a typical installation, the strain gauges are installed on one side of the frame. (Piercey, et al., 2016) (Suominen, et al., 2017) (Adams, 2018)

The ice load acting on the frame is obtained by subtracting the shear strains measured at each end of the instrumented frame span, providing the total force between the sensors. This has the additional benefit that when using traditional electrical (resistance-type) strain gauges, this subtraction can be done within the Wheatstone bridge as shown in Figure 1. Thus, only one measurement channel is required on the amplifier to measure one frame, providing significant cost saving compared to measuring shear at each end of the frame separately and performing the subtraction later in the data processing. The downside of this approach is that any information on load location within the instrumented span is lost, but typically the main interest is the load magnitude, not exact location, making this compromise attractive, especially for ice load monitoring systems as opposed to instrumentation configured for research purposes.

Suominen et al. (2017) developed the theory to show that when the ice load is not centered on the instrumented frame, the frame will rotate and the shear strain on the left and right surfaces of the frame will not be equal. If the shear strain gauges are installed only on one side of the frame, this will result in a measurement error, which can be significant. By instrumenting both sides of the frame, the effect of frame rotation can be removed and measurement accuracy can be improved (Böhm, et al., 2021). Suominen (2018) has also proposed installing the gauges in a crossed configuration, i.e. one gauge on one side of the frame and the other gauge on the other side of the frame to reduce the measurement error.

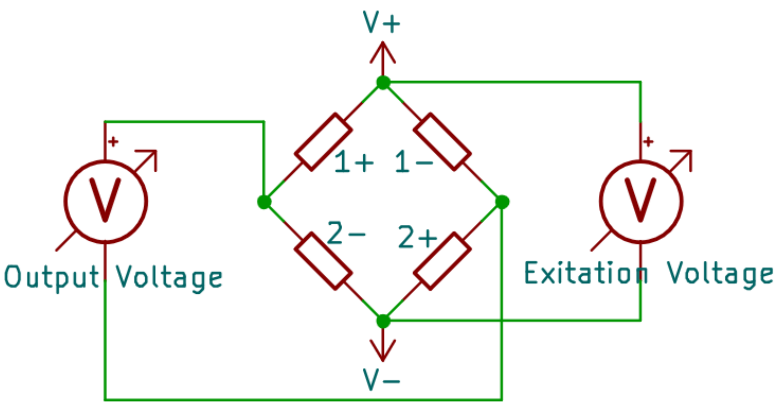

Figure 1. Traditional one-sided instrumentation using electrical strain gauges connected into a Wheatstone full bridge to measure shear difference on a frame. Refer to Figure 5 for gauge locations on the frame.

TWO-SIDED INSTRUMENTATION OF FRAMES

Previously, sensors have not been installed on both sides of the frame, as the thinking has been that the cost increase would be prohibitive. However, if the additional gauges are connected to the same Wheatstone bridge, the additional cost becomes relatively small, as the addition needs only extra gauges and wiring up to junction box, but no additional measurement channels.

In the two-sided instrumentation the gauges on different sides of the frame are connected parallel to each other on each leg of the Wheatstone bridge as shown in Figure 2. Since all the gauges have the same initial resistance and the resistance change due to strain is far less than 1%, the parallel resistance equation can be reduced the to sum divided by four. In this configuration the resistance of each Wheatstone bridge leg is half the average of each two parallel gauge resistances and the output of the bridge is the average of the shear differences on each side of the frame.

If the load on the shell is offset to one side of the frame, the shear differences on each side of the frame due to frame rotation are different. Taking the average removes this error.

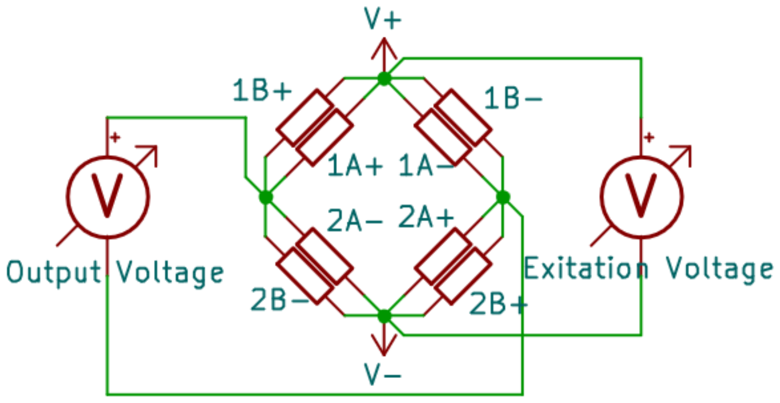

Figure 2. Proposed two-sided instrumentation using electrical strain gauges connected into a Wheatstone full bridge to measure shear difference on a frame. Refer to Figure 5 for gauge locations on the frame.

LABORATORY TESTS

Method

To test different strain gauge setups and improve the methodology, a semi-scale laboratory rig shown in Figure 3 was built. The rig consists of frame, test piece and loading mechanism. The frame was built to be as rigid as practical, while keeping it manoeuvrable with a pallet jack. The test piece was built to resemble the side shell of an icebreaking vessel in scale of approximately 1:2…1:3.

The load was provided by a hydraulic jack, shown in Figure 3. The applied load was measured directly with a ME-Meßsysteme KM115e 200 kN load cell connected via a HBM Quantum MX840B measurement amplifier to a computer as shown in Figure 3. The measurement of the applied load was separate from the tested strain gauge setup, and thus it was possible to evaluate how the tested strain gauge setup captures the applied load. The whole test rig is shown in Figure 3 and the main dimensions of the test piece are shown in Figure 4.

Figure 3. Test rig (left), consisting of frame, test piece, loading device (shown in more detail on right) and measurement setup.

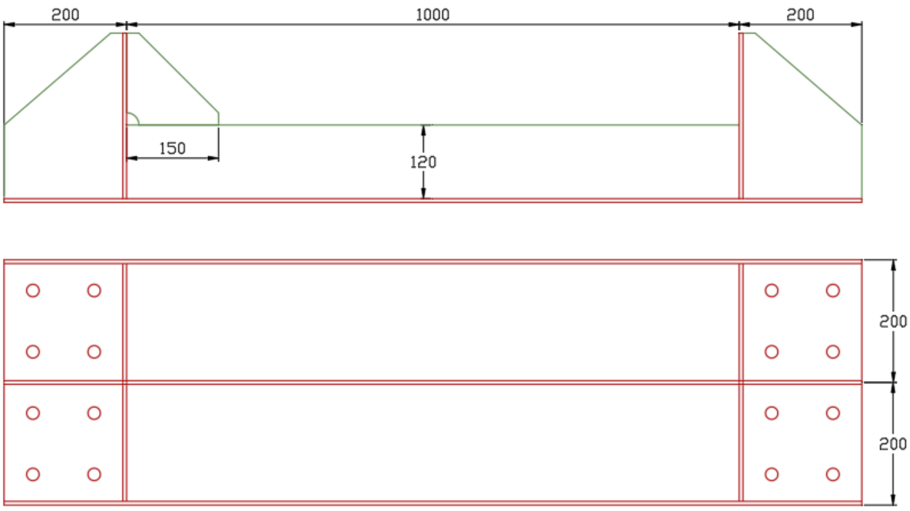

Figure 4. Main dimensions of the test piece. All parts are made from mild steel plate with thickness of 6 mm.

For a typical test, the load was increased in four increments from 0 to 40 kN. The load was spread over an area of 200 x 100 mm with a thick (20 mm) steel plate and softer layers of 20 mm of softwood and 10 mm of rubber to obtain an evenly distributed load. The deflection of the load spreading steel plate was confirmed to be small relative to deflection of the test piece under load. The load location was varied both along the frame (x-direction) and perpendicular to the frame (y-direction), as shown in Figure 5.

Strain gauges were located at both ends of the frame span, at suitable distance from the supporting structure to ensure relatively even stress field. The strain gauge locations are shown in Figure 5. Strain gauges were type HBM XY41-3/350 and were measured with the HBM Quantum MX840B connected to a computer. The tests were made both with the one-sided setup using gauge pairs 1A-2A, 1B-2B and 1A-2B connected as shown in Figure 1, and with the two-sided setup using all four gauges connected as shown in Figure 2.

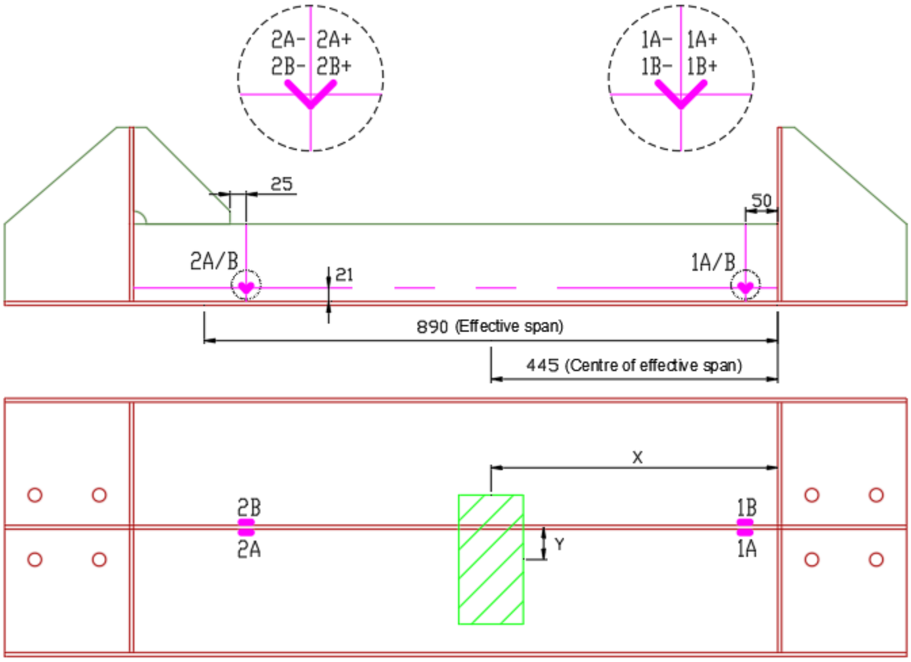

Figure 5. Strain gauge locations, load locations and naming convention.

Results

Results of the laboratory tests with the test rig are shown in Table 1 for the one-sided instrumentation with gauges on the same side (gauge pairs 1A-2A and 1B-2B), in Table 2 for the one-sided instrumentation with crossed gauges (gauge pair 1A-2B) and in Table 3 for the two-sided instrumentation. The results are shown as measured load divided by the applied load.

In ideal case, the measured load would be 100 % of the applied load when the load would be applied completely to the instrumented frame and would decrease in proportion to load division between the frames when load is moved to either side of the instrumented frame. For a structure with identical frames spaced at 200 mm, moving the load in Y-direction by 100 mm should result in even load division between frames, and measured load of 50 % on the instrumented frame. As the test piece is somewhat narrower for practical reasons, the instrumented frame has wider effective flange than adjacent frames and is expected to carry somewhat larger portion of the load.

Table 1. Results of laboratory tests with one-sided instrumentation for gauge pair 1A-2A (left) and gauge pair 1B-2B (right).

X ↓	Y →	-100	0	100
445		22 %	101 %	120 %

X ↓	Y →	-100	0	100
445		122 %	107 %	30 %

Table 2. Results of laboratory tests with one-sided instrumentation, crossed gauges (1A-2B).

X ↓	Y →	-100	0
325		41 %	-
445		71 %	106 %
675		137 %	-

Table 3. Results of laboratory tests with two-sided instrumentation. As the whole setup is symmetrical, load location Y is varied only to one side.

X ↓	Y →	0	50	100
325		100 %	93 %	67 %
445		100 %	94 %	68 %
575		102 %	94 %	71 %
675		104 %	97 %	74 %

Analysis

The results shown in Table 1 confirm that when load is centred on the instrumented frame, the one-sided instrumentation works as it should, measuring the applied load with good accuracy. When the load is moved to the non-instrumented side, the measured loads decrease rapidly, and the one-sided strain gauge setup underestimates the measured load. When the load is moved to the instrumented side, the measured load is higher than the applied load, which is in clear contradiction with the desired behaviour for the measurement system. This aligns with the theory presented by Suominen et al. (2017) and numerical results of Böhm et al. (2021).

The results shown in Table 3 confirm that the two-sided measurement system has significantly better ability to measure the loads correctly. The applied load is measured correctly when the load is centred on the instrumented frame and is decreasing as expected when the load is moved to the side. The laboratory measurements for the two-sided setup were made only by moving load to one side in Y-direction, since the whole setup is symmetrical and there is no reason to expect a difference in results by moving the load to the other side. This aligns with the numerical results of Böhm et al. (2021).

FINITE ELEMENT ANALYSIS

Method

The test piece was modelled in Abaqus/CAE 2021 to analyse the behaviour with finite element method and to form the influence coefficient matrix (ICM), i.e. the calibration factor to convert measured strain difference to a force. The model was made both with shell elements, as is typical for modelling ship structures (Valtonen, et al., 2020), and with solid elements.

For the model with shell elements, mesh size was taken as 5 mm, and element type was S4R, which is a first-order quadrilateral (4-node) general purpose shell elements with reduced integration, hourglass control and finite strain (Dassault, 2021). For the model with solid elements, mesh size was generally taken as 6 mm, and element type was C3D20R, which is a second-order 20-node quadratic brick with reduced integration (Dassault, 2021). On the instrumented frame, the element thickness was reduced to 3 mm, so that two elements through thickness were used. Both models are shown in Figure 7.

The load was applied as an evenly distributed pressure load over an area of 200 mm x 100 mm, example is shown in Figure 6. Pinned boundary conditions were applied at the bolted clamping plates, as shown in Figure 6. Consequently, all elements under the clamping plates were restrained in all degrees of freedom, and the nodes at the edges of the clamping plates were restrained in translational degrees of freedom but were free to rotate.

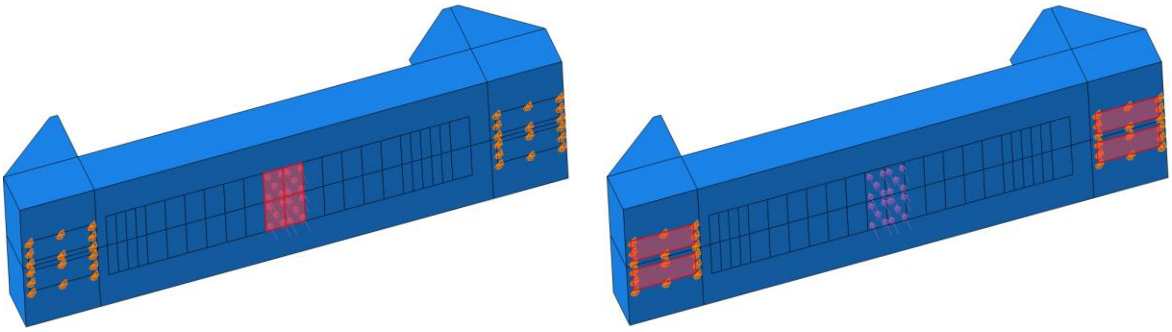

Figure 6. Load (left) and boundary conditions (right) applied to the model.

The analysis was completed with linear elastic domain and small displacements, using Abaqus/Standard 2021 implicit solver. Results were extracted as nodal shear strains at the same coordinate as the strain gauges installed on the laboratory tests. The ICM for the laboratory tests was made with the shell model, by applying the load at X 445 mm and Y 0 mm, i.e. with load centred on the instrumented frame and the effective span.

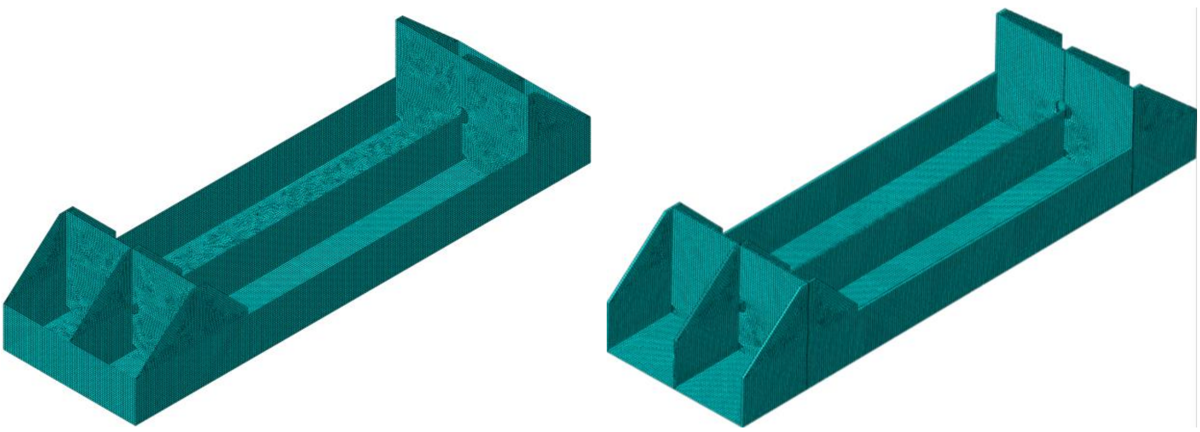

Figure 7. FE model, shell model on left and solid model on right.

Results

Results of the FE analysis with solid element model are shown in Table 4 and Table 5 for the one-sided instrumentation and in Table 6 for the two-sided instrumentation. These are compared to laboratory measurements shown in Table 1, Table 2 and Table 3 in Table 7 and Table 8. Results for shell model are not shown in detail, as it was found that when load is centred on the instrumented frame, the shell model agrees with the solid model and laboratory results, but when the load is offset to side, the shell model is unable to account for the shear stress from the frame rotation and provides erroneous results.

Table 4. Results of FEM analysis with solid elements and one-sided instrumentation with gauges on the same side.

X ↓	Y →	-100	-50	0	50	100
325		119 %	127 %	103 %	62 %	23 %
445		105 %	116 %	101 %	69 %	35 %
575		118 %	125 %	100 %	59 %	21 %
675		144 %	142 %	100 %	41 %	-6 %

Table 5. Results of FEM analysis with solid elements and one-sided instrumentation with crossed gauges.

X ↓	Y →	-100	-50	0	50	100
325		39 %	72 %	103 %	117 %	103 %
445		70 %	93 %	101 %	92 %	69 %
575		102 %	115 %	100 %	69 %	37 %
675		136 %	137 %	100 %	46 %	2 %

Table 6. Results of FEM analysis with solid elements and two-sided instrumentation.

X ↓	Y →	-100	-50	0	50	100
325		71 %	95 %	103 %	95 %	71 %
445		70 %	93 %	101 %	93 %	70 %
575		69 %	92 %	100 %	92 %	69 %
675		69 %	92 %	100 %	92 %	69 %

Table 7. Error of FEM results from the solid model compared to laboratory measurements for one-sided instrumentation with gauges on same side (left) and crossed (right).

X ↓	Y →	-100	0	100
445, 1A-2A		+35 %	-3 %	-13 %
445, 1B-2B		-30 %	-6 %	-14 %

X ↓	Y →	-100	0
325		-6 %	-
445		0 %	-5 %
675		-1 %	-

Table 8. Error of FEM results from the solid model compared to laboratory measurements for two-sided instrumentation.

X ↓	Y →	0	50	100
325		+3 %	+2 %	+7 %
445		0 %	-2 %	+3 %
575		-2 %	-2 %	-2 %
675		-4 %	-5 %	-7 %

Analysis

The results shown in Table 4 clearly demonstrate that the one-sided instrumentation results in a significant error for predicting the ice load when the load is not centred on the instrumented frame. Using crossed gauges, so that one gauge is on one side and the other gauge on the other side of the frame improves the response somewhat, as seen in Table 5, but the errors remain still significant and in some cases the ice load is overestimated.

As Suominen (2018) noted, the peak ice load tends to move along the ship hull over several frames and have relatively similar peak values on each frame. Thus, if the instrumentation has a tendency to overestimate a load that is offset from the measured frame by 10 to 40 %, the measured maximum load is likely to be overestimated by the same amount when the load is measured using a single frame. For typical instrumentation with two or more adjacent frames instrumented, this error is somewhat mitigated by the influence of the adjacent frames in the

ICM, as demonstrated by Böhm et al. (2021). Further research into the accuracy when several frames are instrumented would be recommended.

The results shown in Table 6 show that two-sided instrumentation overcomes this issue and will not overestimate the ice load regardless of load position. Moreover, if it is assumed that the peak load moves horizontally over the frames and peak value is applied at each location at some time instance, two-sided instrumentation will measure the correct maximum load, unlike the one-sided instrumentation.

DISCUSSION

The results shown in Table 7 and Table 8 demonstrate good agreement between the solid FEM model and laboratory measurements for two-sided and crossed one-sided instrumentation, as well as traditional one-sided instrumentation when the load is centred on the instrumented frame. For one-sided instrumentation with load offset to either side, there is some difference between FEM results and laboratory measurements, but both agree that the measured load differs significantly from the applied load and the measurement system produces erroneous results. Using finer mesh with 3 to 5 layers of solid elements over material thickness might improve the accuracy of the FEM analysis and reduce difference between the FEM and the laboratory results but would not change the conclusion that one-sided instrumentation is not able to measure offset loads correctly.

It should be noted that the presented method of arranging two-sided instrumentation with relatively small cost increase is applicable to traditional electrical strain gauges which can be combined into one Wheatstone bridge / measurement channel. With fibre-optic strain gauges, strain in each direction is measured separately, and all mathematical operations to add and subtract strains are done on the computer. As strain measured is equated to a change in wavelength and the number of discrete wavelength signals per channel of the interrogator are limited, this may lead to an increase in the required interrogator channels for a fibre-optic configuration.

An additional benefit of the two-sided instrumentation is the degree of redundancy provided by double gauges. While it is not possible to automatically change the electrical connection to one-sided in case of failure of a single gauge, it is significantly easier to reconfigure the measurement system to a one-sided connection in field conditions than to repair a traditional one-sided measurement system by replacing the gauge. Changing a two-sided system to a one-sided configuration requires only accessing the junction box and reconnecting cables at the connection strip. Repairing a broken strain gauge for a one-sided installation requires cleaning the installation location, glueing in a new gauge, soldering cables and protecting the installation with resin/putty. This is not easy or in many cases not even possible when the ship is in service, due to cold temperature making it very complicated to obtain conditions suitable for curing of the glue and protection. While changing a two-sided configuration to a one-sided will degrade measurement accuracy, it will still allow the system to be used at least with limited accuracy, instead of complete loss of the measurement point.

Practical experience

Aker Arctic, ABB and Ponant have collaborated on ice load measurements on Ponant's icebreaking cruise ship Le Commandant Charcot (Aker Arctic, 2025). As part of the collaboration, Aker Arctic installed strain gauges on Le Commandant Charcot to measure ice loads on the hull when navigating both ahead and astern. This installation was made using the two-sided configuration discussed in this paper. After analysing the measurement data from the first season of operation, it can be concluded that the system is working as expected.

Compared to a traditional one-sided setup, the extra work needed was installing a second set of gauges on each instrumented frame, and cabling these to the junction boxes located on each frame. Overall, this added about 20 % to the installation hours and about 10 % to the cost of the system, which can be considered a reasonable price for the improved accuracy and certainty of measuring the actual maximum values for the ice load.

Installation work must be carried out with care to ensure accurate gauge positioning which is crucial for overall accuracy of the measurement system (Veltheim, 2025), but it can be made easier with proper preparations. Good reference drawings and jigs for marking gauge locations eliminate unnecessary measuring and calculating on the site, making overall installation more efficient and faster.

CONCLUSIONS

The laboratory measurements and finite element analysis presented in this paper confirm the theory of Suominen et al. (2017) and numerical results of Böhm et al. (2021). If ice loads are measured with the traditional setup of two shear gauges on a frame and installed on one side of the frame, the system measures the ice load accurately as long as the load is centred on the instrumented frame. When the load is offset from the instrumented frame, the system will either under or overestimate the actual ice load. The most serious error is the overestimation of the ice load, which may be up to 40 %, which, when combined with the movement of the load along the ship hull, can lead to overestimation of the maximum load.

This issue can be somewhat mitigated by installing the sensors in crossed arrangement as proposed by Suominen (2018). The crossed configuration decreases the error in all cases compared to one-sided instrumentation, but the errors remain significant, and, in some cases, the load is still overestimated by up to 35 %.

Two-sided instrumentation eliminated these issues and measured the load accurately regardless of the load location. When executed by connecting all shear gauges into the same Wheatstone bridge using the connection shown in this paper, the additional cost of two-sided instrumentation becomes acceptable. Two-sided instrumentation has been used in ice load measurement system installed on Le Commandant Charcot in 2024. Based on the experience from installation and analysis of first data, the system works as expected.

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