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Enhanced Influence Coefficient Matrix for Estimation of Local Ice Loads on IBRV ARAON

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ABSTRACT

A new approach for deriving an influence coefficient matrix is adopted for estimation of local ice loads on the hull plates of the IBRV ARAON. So far the influence coefficient representing the relation between the measured strains and ice pressure on the hull plate of the ship by calculating the von Mises equivalent stresses, which sometimes misleads the actual hull ice loads. The directions of the calculated stress are not consistent with the ice loads on the hull plate. In this paper, three in-plane stress components including shear stress measured/calculated from fiber optic sensors and the rosette type strain gauges installed inside the ship's hull plate are utilized to derive the relationship with local ice load components in three directions. An enhanced influence coefficient matrix is assembled to give the actual ice loads in longitudinal, lateral and vertical directions during ship-ice interaction.

KEY WORDS: Local ice loads; Influence coefficient matrix; Icebreaking research vessel ARAON

Introduction

The practical approach to estimate the local ice load on a vessel during icebreaking process is to measure directly at the contact location with the sea ice, however it is very difficult because of the lack of proper measuring sensors on the outside panel of the ship's hull. Therefore, strain measuring sensors are usually installed inside the hull plate indirectly to measure the deformation due to sea-ice interaction, then the measured strains are converted to hull stresses and finally the ice load is calculated. During this procedure, a method of the influence coefficient matrix (ICM) is frequently adopted to obtain a relationship between the hull stresses and the local ice load (Lee et al., 2013).

The influence coefficient matrix representing the relationship between the input forces and the resulting responses of a given structural system can be obtained by a full-scale experiment or simply by using a finite element analysis of the system. So far in estimation of local ice loads, the influence coefficient matrix uses a relationship between the hull stresses and ice pressure acting normal to hull structure. Here, von Mises equivalent stresses usually represents the calculated hull stresses. However this sometimes misleads the actual hull responses because the directions of the calculated von Mises stress are not necessarily consistent with the ice loads on the ship's hull.

To overcome this inconsistency, instead of von Mises equivalent stresses, hull stresses for all in-plane directions can be used. In this paper, three in-plane stress components including shear stress measured/calculated from fiber optic sensors and the rosette type strain gauges installed inside the ship's hull are utilized to derive the ice loads in three directions. Therefore an enhanced influence coefficient matrix can be assembled to give the actual hull responses. The ice field strain gauge data recorded during the IBRV ARAON's 2019 Antarctic voyage was analyzed to retrieve the patterns and the magnitude of local ice load using the new approach of the enhanced influence coefficient matrix.

The method of ICM derivation relating local ice pressure to hull stresses via von Mises equivalent stress is given in eq.(1). This is most frequently used algorithm in estimation of ice load on ship's hull, however von Mises equivalent stress does not represent the actual stress components. It always produces positive values (i.e. tensile stresses) and it cannot be used as an index to indicate the direction of stresses

$$[C]\{p\}^T = \{\sigma_{eq}\}^T \quad \text{or inversely} \quad \{p\}^T = [C]^{-1}\{\sigma_{eq}\}^T$$
(1)

where $[C]$ is a so-called influence coefficient matrix, p, the ice pressure normal to hull plate, and σ_{eq}, the von Mises equivalent stress calculated from strain gauge measurement.

For improvement of ICM, a method using stresses in two directions was developed. For example as shown in eq.(2), Truong and Jang (2021) derived an influence coefficient matrix using two stresses in the x- and y-direction respectively instead of using von Mises equivalent stress.

$$[C]\{p\}^T = \{\sigma_X\ \sigma_Y\}^T \tag{2}$$

where the matrix $[C]$ is not symmetric and it can be dealt with a special pseudo-inverse technique.

The above two methods in eq.(1) and eq.(2) calculate ICM based on ice pressure acting normal to the hull plate. In the actual field condition, the direction of ice load acting on hull plate varies depending on the location and interaction processes between the hull shape and ice features. Therefore it may be more appropriate to consider any possible ice loading directions at the contact point. Strain sensors installed inside the ARAON's hull plate are mostly 3-axis rosette type, hence it is more useful to utilize all three strain measurement at the same time. In this paper, a new enhanced influence coefficient matrix is presented as in eq.(3).

$$[C]\{F_X\ F_Y\ F_Z\}^T = \{\sigma_X\ \sigma_Y\ \tau_{XY}\}^T \quad \text{or inversely} \quad \{F_X\ F_Y\ F_Z\}^T = [C]^{-1}\{\sigma_X\ \sigma_Y\ \tau_{XY}\}^T \tag{3}$$

Again $[C]$ is the influence coefficient matrix. Unlike the above two cases, the size of ICM is $3n \times 3n$, when measured in n divided areas. By multiplying the inverse matrix of ICM to strains/stresses measured from sensors, the components of ice load at each measuring location can be estimated.

Evaluation of Influence Coefficient Matrix for ARAON's Hull Plate

In December, 2019, the Korean icebreaking research vessel ARAON conducted an ice field test in the Ross Sea, Antarctica. During the field test, extensive amount of strain data was recorded from strain gauges and also fiber optic sensors installed on the inside hull plate of a thruster room near the ARAON's bow area. Information such as ship motion including ship speed, ice properties and ice thickness were also collected from various sensors and the integrated monitoring system. For the analysis of local ice loads, the influence coefficient matrix is derived based on the approach presented in this paper.

Figure 1 shows the structural section for the finite element modeling. The dark shaded region in the left depicts the area for sensor instrumentation. The x-axis is for the longitudinal direction, y-axis for lateral direction and z-axis is for vertical direction respectively.

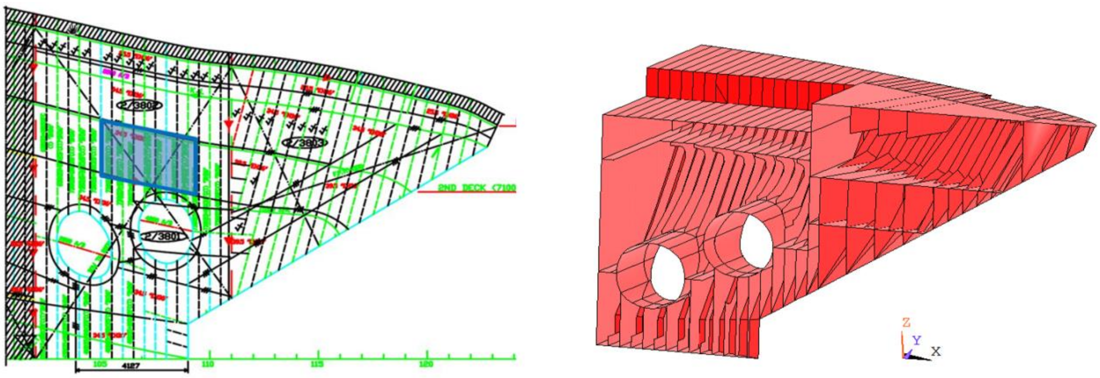

Figure 1. Location of instrumented area in the bow thruster room (Left) and the structural analysis model (Right)

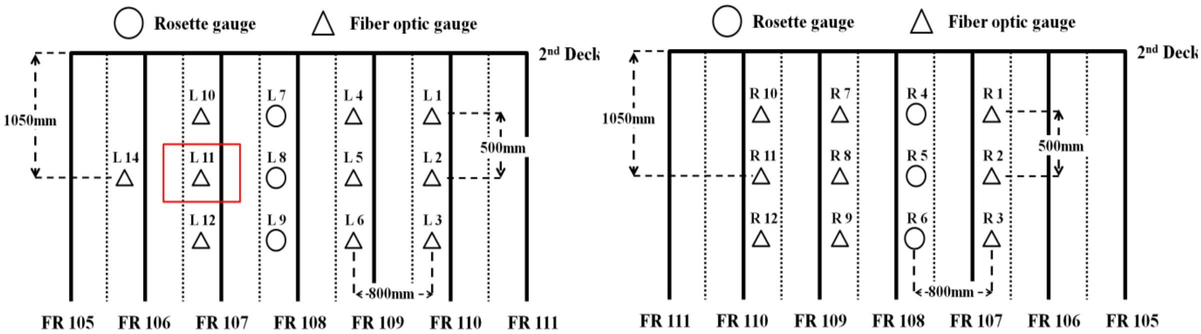

Figure 2. Position of the installed strain sensors on the hull plates of the ARAON in the port and starboard sides respectively

A total of 13 rosette strain gages and fiber optic sensors are installed in the port side and 12 rosette strain gages and fiber optic sensors are installed in the starboard side as shown in Figure 2. The area covered by one sensor is marked by a rectangular box and is equal to $0.4\,\mathrm{m}^2$. Finally, the enhanced influence coefficient matrix can be derived from repeated finite element structural analysis and is comprised of 39×39 matrix for the port side and 36×36 for starboard side.

Data Analysis for Local Ice Load during the ARAON's 2019 Antarctic Voyage

The ice field strain gauge data recorded during the IBRV ARAON's 2019 Antarctic voyage is analyzed to retrieve the patterns and the magnitude of local ice load using the enhanced influence coefficient matrix. Figure 3 shows the typical icebreaking pattern and its corresponding level ice condition during the ARAON's 2019 Antarctic voyage in the south of Ross Sea.

Figure 3. Typical icebreaking pattern and its corresponding level ice condition

Approximately one of 80 minutes strain data set is selected for the analysis. For analysis, only the port side data is considered. Ship speed is measured using a GPS installed outside the hull structure near centerline of the ship. Information for sea ice thicknesses is obtained using image processing software and video images of the broken ice pieces (Park et al., 2014). The ice sheet thickness using this software is observed to be 0.5 to 1.8 meters although the all the thickness data is not known.

The ice load components in three directions estimated using the enhanced influence coefficient matrix is shown in Figure 4. Assuming a flat plate and a unit normal vector, the ice load F_n normal to the plate can be calculated and is shown in Figure 5. Peak ice loads of 0.4 MN or higher are plotted in the figure as a categorized 'event'. Total number of events in this data set is 1,152 and peak ice loads are shown in Figure 6 with ship speed as a horizontal axis. It is found that the maximum peak ice load is 3.37MN with the ship speed 7.35 m/s at that instance. Dividing the maximum peak ice load by the measurement area, $4.8\,\mathrm{m}^2$, the maximum peak ice pressure is 0.702 MPa.

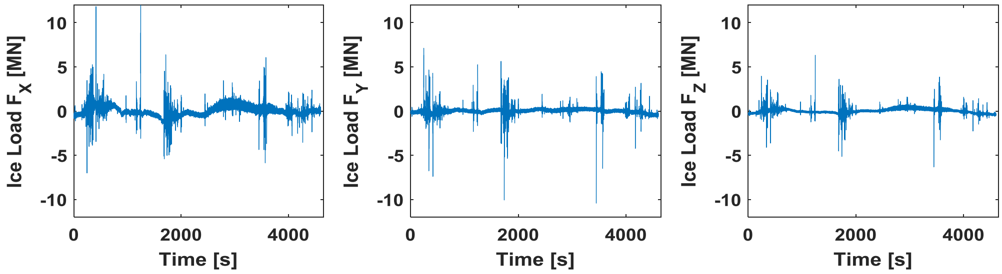

Figure 4. Patterns of the calculated ice load components (port side only) in each direction

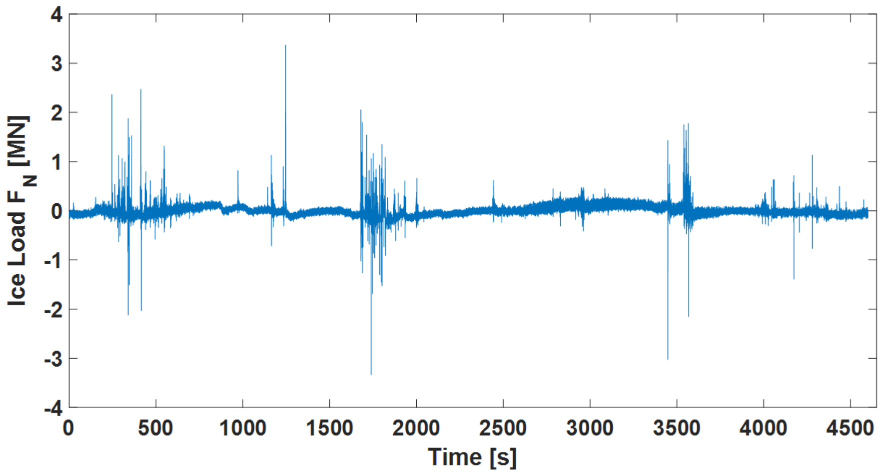

Figure 5. Patterns of the summed ice load normal to the surface of the plate (port side only)

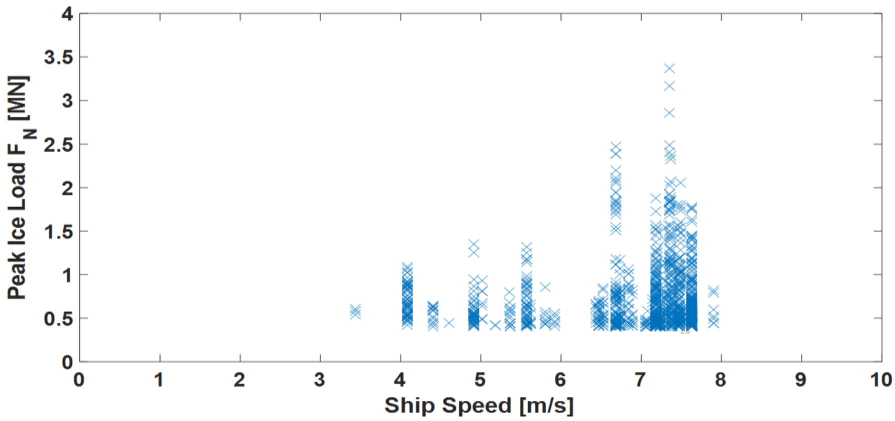

Figure 6. Peak ice load (port side only) vs. ship speed

Conclusions

In this paper, a new approach to calculate the influence coefficient matrix is presented and the ice field strain gauge data recorded during the IBRV ARAON's 2019 Antarctic voyage is analyzed. Following conclusions can be drawn:

1) The components of local ice load can be estimated with the use of enhanced ICM. The new approach captures all the important patterns of the ice loads in time series and the magnitude of local ice load can be obtained in a reasonable range using the new approach.

2) The ice load in the vertical direction (F_Z) may be connected to bow impact or beaching process and also the load in the longitudinal direction (F_X) may be used for the determination of ice resistance, if measurement data is available for the entire hull.

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