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METHOD FOR RECOVERY OF ICE LOAD PARAMETERS BASED ON STRAIN GAUGE MEASUREMENTS

Leonid Kniazev [1], Vladimir Tryaskin [1], Alexey Dudal [2]
[1]State Marine Technical University, Saint Petersburg, RUSSIA
[2] Bureau Veritas, Neuilly-sur-Seine, FRANCE

ABSTRACT
Nowadays the leading role in the Arctic region belongs to large tonnage ship especially LNG carriers and oil tankers. These vessels serve the purpose of connecting European and Asian markets. However, the lack of experience in operating of large tonnage vessels in ice covered waters requires the additional researches to ensure appropriate ship hull reinforcement. The full-scale strain gauge measurements allow investigation of ship hull response to ice loads and significantly reduce the risk of damages due to ice collision. Nevertheless, the full-scale strain gauge measurements have some drawbacks. During shipping in ice an actual ice load can be applied out of sensors thus the maximum value of the internal stresses cannot be read.
The present work proposes a method for recovery of ice load and determination of real location of contact zone basing on internal stress measurements in side grillage. The method builds on solution of multiparametric optimization problem. In order to obtain a goal function, the regression dependencies of ice load parameters should be derived using design of experiment technique. The regression coefficients are calculated using data of hull structure response in elastic behavior, finite element package and numerical tool developed by the authors. The ship and ice interaction is described complying with hydrodynamic model.
The proposed method allows estimation of real values of internal stresses in side structures of ice-going vessels and can be used for prediction of ice loads.

INTRODUCTION
The recovery of ice load parameters, such as: ice pressure, total contact force, load patch size; can be important for the analysis of full-scale measurements results. Usually the stresses exerted in the hull structure of the ice-going vessels by ice loads do not exceed elastic limit. The ice loads resulting in plastic deformation of ship structures are of low probability and can be considered as the accidents (Lindberg, 1981). Therefore the strain sensors can be used for the measurements of hull structure response to ice loads. The strain sensors measure linear elastic deflections of hull structure elements due to ice loads. Existing calibration methods allow definition of stress-strain ratio. However, the parameters of ice load are usually undefined. In order to estimate these parameters several methods can be used with a certain level of accuracy (Timofeev et al., 1999), (Mironov et al.,2008).

METHODOLOGY
The method for recovery of values of ice load parameters proposed in the present paper builds on a nonlinear programming problem (Himmelblau, 1972), where the set of unknown real variables is:

$$\mathbf{X} = \left\{ x_i \right\}^T, i = 1,...,k . \tag{1}$$

Solution can be found by minimizing a goal function GF (**X**) subject to equality and/or inequality constraints

$$h_j(\mathbf{X}) = 0,\ j = 1,\ldots,m \qquad (2)$$

$$g_j(\mathbf{X}) \geq 0,\ j = 1,\ldots,n \qquad (3)$$

and boundary conditions

$$(x_i)_{\min} \leq x_i \leq (x_i)_{\max} \qquad (4)$$

The problem can be solved by using software for nonlinear optimization.
Five parameters of ice load (k=5) should be considered as unknown variables. They are:

- Central coordinates of ice load patch $x_1 = X_c,\ x_2 = Z_c$;
- Height and length of the contact zone $x_3 = b_s,\ x_4 = l_s$;
- Ice pressure $x_5 = p_0$.

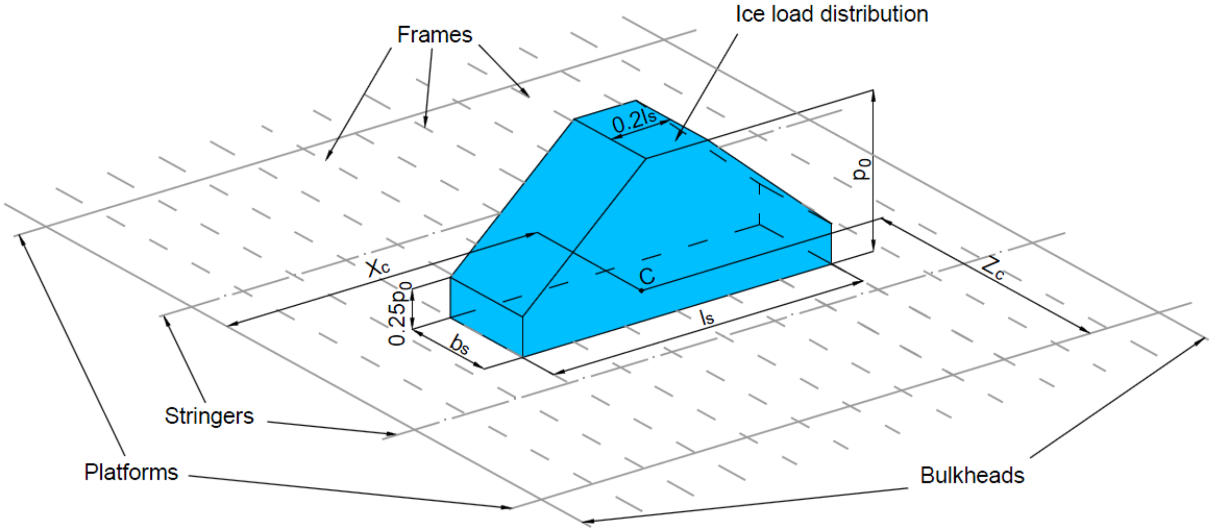

Figure 1: Local ice load acting on ship hull.

Goal function can be taken as follow:

$$GF(\mathbf{X}) = \sum_{u=1}^{ns}\left(\sigma_u - \hat{\sigma}_u(\mathbf{X})\right)^2, \qquad (5)$$

where

ns is the number of points where sensors are installed,

σ_u is the value of stress in *u*-point measured by *u*-sensor,

$\hat{\sigma}_u(\mathbf{X})$ is the value of flexural stresses, in *u*-point defined by analysis of internal forces, when the ice load parameters (X_c , Z_c , b_s and l_s) are determined by the vector $\mathbf{X} = \{x_i\}^T, i = 1,\ldots,k$ are the components for the current step of iterative optimization process.

The goal function is too complex for the analytical solution and requires involvement of special or universal software. The goal function can be presented as a regression dependency using software for experimental design (Tryaskin, 1990).

The shape of ice load distribution can be trapezoidal as depicted in Figure 1. The assumed shape complies with the hydrodynamic model of ice load failure (Kurdyumov & Khesin, 1976). The $x_5 = p_0$ is assumed to be maximal ice pressure in the middle of ice load patch.
The stresses in specified point of the structure can be calculated by using numerical tool built on conception of beam idealization of side grillage and conception of attached flange for the beams. The tool can be launched in iterative mode for the calculation of the goal function value. The single calculation takes about a split second. Owning to conventionality of structural idealization, the recovered ice load parameters are approximate and can be described by a certain level of accuracy.
In case of finite element modeling of hull structure by plate elements, the design of experiment technique should be applied instead of iterative procedure. The accuracy of ice load parameters assessment depends on accuracy of goal function calculation by regression dependency. The design of experiment technique can be also used in case of beam idealization of hull structure.
According to recommendations given by (Tryaskin, 1990), the accuracy of regression models can be assessed by comparison of the results received from numerical experiment and solution of regression equation. The difference should not exceed 2.5 – 5.0% for the hull structure design. Owing to stochastic nature of ice load parameters, the error of regression model can be taken up to 10%.
The wide variability interval and significant nonlinearity of response function do not allow formulation of accurate regression model by design of experiment technique. The solution of such task requires increment of polynomial order. As a result the number of numerical experiments will be increased. Therefore the increment of polynomial order can be useless. The application of piecewise smooth function is more efficient as it allows complication of analytical form of the function only for the intervals of significant outliers (Fedorov, 1969). In some cases the logarithmic transformation of function values "(6)" is efficient (Tryaskin, 1990).

$$\hat{\sigma}_u(\mathbf{X}) = \exp\left\{ b_0 + \sum_{i=1}^{k} b_i x_{iu} + \sum_{i=1}^{k} b_{ii} x_{iu}^2 + \sum_{j>i} b_{ij} x_{iu} x_{ju} + \sum_{m>j>i} b_{ijm} x_{iu} x_{ju} x_{mu} + \dots \right\} \qquad (6)$$

Application of goal function "(5)" is a quite stringent condition for recovery of ice load parameters. The stiffness factor depends on number of simultaneously considered sensors.
The physical conditions and geometry of ice can be included as constraint equations. For instance, subject to ship hull impact with the rounded ice edge the dependency of contact zone length on its height can be written as an equality constraint "(7)":

$$h(\mathbf{X}) = x_4 - 1.6 \cdot \sqrt{2R \cdot x_3 \cdot \sin\beta(x_1, x_2)} = 0, \qquad (7)$$

where

R is the radius of the rounded ice edge,

$\beta(x_1, x_2)$ is the ship hull inclination angle at the point of impact located in the middle of the load patch and the coordinates x_1 and x_2.

If the measurement equipment allows monitoring of ice thickness, the maximal height of the contact zone corresponds to maximum indentation of ship hull into the ice and can be restricted by inequality constraint "(8)"

$$g(\mathbf{X}) = H - x_3 \cdot \cos\beta(x_1, x_2) \geq 0. \qquad (8)$$

where

H is the ice thickness.

The boundary conditions "(4)" depends on design draft, longitudinal coordinate of the hull structure, strain gauge sensors location, etc. It defines the range of the variables.

The dangerous ice loads usually occurs due to dynamic impact against ice flow or edge of the channel. Navigation in ice field does not exert high stresses in hull structures, but it generates noise field. To exclude inappreciable ice loads from the analysis, the threshold can be set as a ratio of stress in hull structure to yield limit. For instance, the values exceeding $0.1R_{eH}$ can be considered for the analysis of the experimental data. This assumption allows cut-off of the noise field.

SIMULATION

Simulation description

Let's consider hull structure of bow region to give an example for application of proposed method for recovery of ice load parameters. Let's assume that considered hull structure is transversely framed. The strain sensors are installed at the attached flanges of ordinary and intermediate frames and log out linear deformation of attached flanges or stresses due to tension or compression.

The design stresses can be defined by formula:

$$\widehat{\sigma}_u\left(\mathbf{X}\right)=\frac{M_u\left(\mathbf{X}\right)}{W}=\frac{k_{Mu}\cdot Q\cdot l}{W}=\frac{k_{Mu}\left(x_1,...,x_4\right)\cdot x_5\cdot x_3\cdot a\cdot l}{W}, \qquad (9)$$

where

$M_u\left(\mathbf{X}\right)=k_{Mu}\cdot Q\cdot l$ is the design bending moment in a point *u* fitted by strain gauge sensor,

$k_{Mu}\left(x_1,...,x_4\right)$ is the dimensionless coefficient of design bending moment in a point *u* fitted by strain gauge sensor,

$Q=x_5\cdot x_3\cdot a$ is the design ice load,

a is the frame spacing,

l is the beam span,

W is the section modulus of frame at the level of the sensor.

We assume that stresses in the beams do not exceed yield limit and linearly depend on ice load pressure "p_0". Therefore the dimensionless coefficients of bending moment do not depend on value of the pressure.

A considered transversely framed hull structure was assumed to be located within ice belt region. The considered structure consists of ordinary and intermediate frames and intercostal stringers. The elements were assumed to be T-section beams. The face plates width and thickness are equal to 100 mm and 30 mm respectively and the web height and thickness are equal to 380 mm and 16 mm respectively. The width and thickness of attached flange equal 380 mm and 24 mm respectively. The transversal bulkheads and platforms support the considered hull structure. The fixed supports join side stringers and frames with the transversal bulkheads and platforms. The spans, spacing and dimensions of considered structure in meters are depicted in Figure 2.

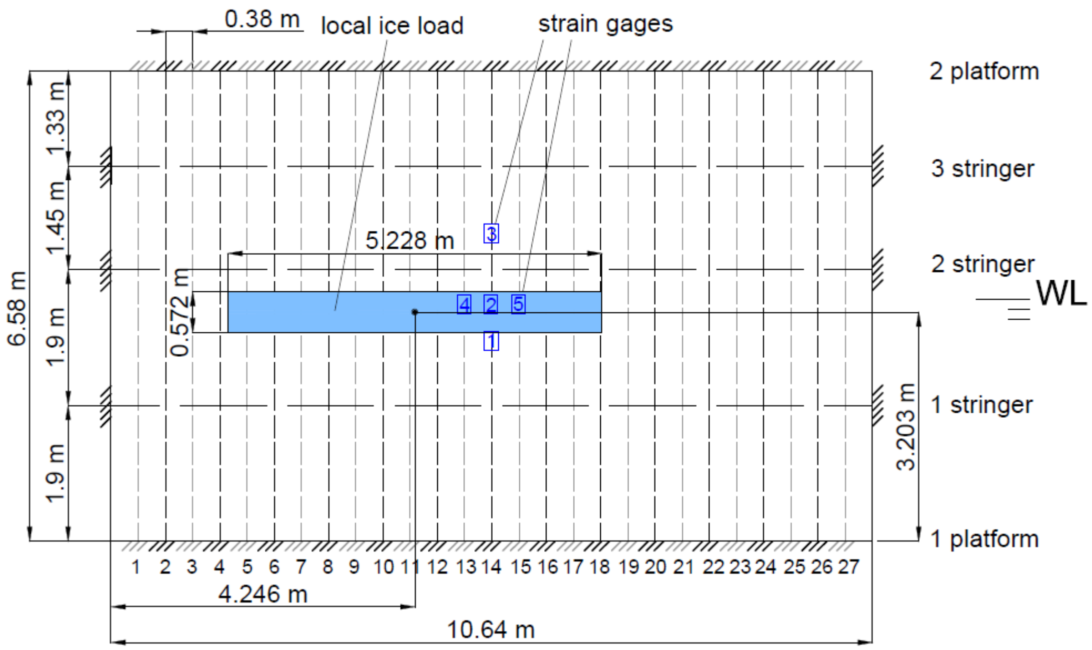

Figure 2. Scheme of considered hull structure.

Simulation results

The numerical experiment was performed with the use of in-house software intended for analysis of internal forces exerted by local ice loads on the elements of hull structure (Kurdyumov & Tryaskin, 1979). The algorithm of the software is based on a beam idealization of hull structure grillage and applies a method of equating of deflections for solution of static indeterminacy. The bending and shearing strain influence are taken into account.

Analysis of internal stresses with the various values of ice load parameters allowed determination the quadratic regression dependencies of bending moment coefficients on X_c , Z_c , b_s and l_s in the form "(10)" using design of experiment technique.

$$k_{M\,u}\left(\mathbf{X}\right) = b_0 + \sum b_i x_{iu} + \sum b_{ii} x_{iu}^2 + \sum b_{ij} x_{iu} x_{ju} \qquad (10)$$

The bending moment coefficients were calculated in five points as shown in figure 2. The points were assumed to be the locations of the strain sensors, which measured flexural stresses in the face plates of the frames. To obtain a sufficient accuracy of the regression models, the range of the ice load parameters (X_c , Z_c , b_s and l_s) variation was narrowed down. The range for ice pressure variation was chosen complying with condition "(11)".

$$0.25 R_{eH} \le \sigma_{\max} \le 0.75 R_{eH} \,, \qquad (11)$$

where

$\sigma_{\max}$ is the maximal stress in ship structure,

R_{eH} is the yield stress of the steel and is assumed to be equal to 315 MPa.

Table 1. Variability of ice load parameters

Ice load parameter	***b_s (m)***	***l_s (m)***	***X_c (m)***	***Z_c (m)***	***p_0 (MPa)***
Minimum value	0.50	4.56	3.80	3.13	3.12
Maximum value	1.00	9.12	6.84	3.63	9.36

The obtained regression dependencies $k_{Mi}(\mathbf{X})$ allow derivation of objective function complying with formula “(9)”. Stresses measured by strain gauges were modeled with the values of stresses σ_u defined with the use of described in-house software. The direct values of stresses were obtained for the case, when an ice load could be described by the following set of parameters shown in Figure 2: b_s = 0.573 m; l_s = 5.228 m; X_c = 4.245 m; Z_c = 3.203 m; p_0 = 5.590 MPa. The stresses σ_u in points 1-5 were respectively: σ_1 = 109.49 MPa; σ_2 = 141.08 MPa; σ_3 = 95.04 MPa; σ_4=157.01MPa; σ_5 = 122.04 MPa.
The results of the case study are presented in table 2. The obtained values of recovered ice load parameters show good efficiency of described method.

Table 2. The results of the ice load parameters comparison

	b_s *(m)*	l_s *(m)*	X_c *(m)*	Z_c *(m)*	p_0 *(MPa)*
Initial data	0.5732	5.2278	4.2452	3.2032	5.5900
Calculation results	0.6224	5.2773	3.9581	3.2306	5.4873
Error (%)	7.89	0.94	7.25	0.85	1.84

CONCLUSION

The proposed methodology for recovery of ice load parameters demonstrates a general approach for backtracking ice loading events from strain gauge measurements using multiparametric optimization. This approach gives a conventional accuracy of simulation and can be improved in future, taken into account a range of loading cases and different sensor positions.
To increase an accuracy of the calculation, the probabilistic approach should be applied. Particularly, the cross section modulus of the beam should be calculated accounting for corrosion and abrasion of the beams and shell plating (effective flange), and actual area of the cross section which can be left due to manufacturing tolerance. The ice edge geometry included into constraints “(7)” and “(8)” will be also stochastic variables.
Therefore the task can be solved using simulation method. The values of unknown parameters can be modelled by random number generator. It allows derivation the statistical laws of ice load parameters distribution.

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