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DESIGN ESTIMATION OF THE RELIABILITY PARAMETERS FOR ICE BELT STRUCTURES

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ABSTRACT

The paper describes general approaches to a design assessment of reliability of metal ice belt structures. Two approaches are under consideration: a priori and posteriori. The main part of the paper focuses on the analysis of factors which are expedient to take into account in the frame of priori approach. These factors are a stochastic nature of ice load parameters and a random character of structure material properties. A general algorithm of the safe analysis is described which takes into consideration the cummulation of permanent deflection in the structure members.

1. INTRODUCTION

It is common practice to recognize the reliability in a broad and a narrow sense [Kryzhevich G.B., 1995]. The reliability in a broad sense is a set of properties which belong to some technical equipment. These properties describe the technical equipment quality and its suitability for operation. A comparative analysis demands using quantitative parameters which can describe in general the technical equipment. A set of such parameters is called reliability indicators (reliability in narrow sense). The following indicators of reliability for analyzing of the ice belt structures can be used:

– reliability in a narrow sense is the probability of safe structure operation during the prescribed period [Chuvikovski, V.S. and Palyi, O.M.; 1965], [Kryzhevich, G.B.; 1995]. Such determination requires to define the term "failure". A failure is an event for which probability is predicted. The formalization of the "failure" event is one of the elements for the reliability prediction.

– durability (service life) can be determined as a probability distribution function for the time from the beginning of operation to the failure.

This paper describes an approach to the reliability indicator calculation for the ice belt structures. Ice belt is a hull region which resists to the local ice loads due to ice/hull contact. The material of ice belt structure is usually metal or concrete. Only metal structures are under considered.

There are two fundamental approaches to estimate the reliability indicators: priori and posteriori. The algorithms based on the posteriori approach use data on the structural damages obtained from operational experience. The data are processed statistically to calculate the reliability values. The shell drawings can be used as an information source. Such drawings with marks in a damaged region are typically produced after examining the hull in the dock. Publications [ISOPE, Project 1.5.5; 1995], [Kulesh, V. et al; 1998] are devoted to the methods and results of statistical estimates of reliability.

The ice belt can deform plastically during ordinary operation. The most advanced priori procedures for reliability estimation were developed for the elastically deformed structures and fatigue cracks.

The subject of this presentation can be formulated as follows:

– to describe the peculiarities influencing the stochastic response of the ice belt structures and propose the approaches to a formalized description for the purposes of calculating the reliability indicators;

– to analyze the failure criteria using plastically deformed structures based on the numerical methods and computer technology;

– to describe the procedures for calculation of ice belt reliability, which take into account the aforementioned peculiarities.

2. FACTORS INFLUENCING THE STOCHASTIC RESPONSE OF THE ICE BELT STRUCTURE

It is possible to point out several factors which make random values the indicators of the structure operation:

1. Technological factors include dispersion of metal plates thickness, geometrical size of rolled profiles, defects of welding and random fields of the residual weld stresses. The quality control in metallurgical industry allow not to take into account the dispersion of geometrical sizes of plates and profile for shipbuilding. The consideration of the defects of welding and the residual stress fields is a complex problem which beyond this presentation. Further discussion assumes that the technological factors are neglected for the evaluation of the reliability indicators.

2. Dispersion of material properties. The values describing the strength of material of the hull structures (yield stresses, tensile stress, strain characteristics etc.) and prescribed in advanced for the strength analysis, have actually a significant dispersion. This dispersion can be taken into consideration in the suggested approach. The only assumption, which is worthwhile, is uniformity of material properties throughout the structure members. It means that all structure members are manufactured from certain steel and have the same material parameters. These material parameters present in turn, random values.

3. A stochastic nature of operational loads determines mainly the dispersion of parameters of the structure response. There are three approaches for estimating the probabilistic parameters of ice loads. The aforementioned approaches are discussed below. They are quite universal.

2.1. Dispersion of material properties

There is not enough information on the parameters of ship structure steel in literature. This can be due to uncertainties of using such data. Chuvikovski, V.S. and Palyi, O.M.; [1965] mentioned the necessity of using this information. Only one parameter of steel is used nowdays. It is the yield stress σ_y. The study is devoted to the plastically deforming structure. Therefore additional parameters on the general strain-stress diagram: tensile strength σ_u, strain corresponding to yield ε_0 (usually $\varepsilon_0 \approx 0.002$) and strain corresponding to tensile strength δ_0 are involved. Information on the distribution function of σ_y and σ_u could also be applied. There is no information about the stochastic distributions of ε_0 and δ_0 in literature. That is why ε_0 and δ_0 are fixed for the prescribed steel grade. The necessity for considering of σ_u and δ_0 for the strength analysis in the past yield region is confirmed by numerical investigations. The results of investigation are shown on fig. 1.

a)

b)

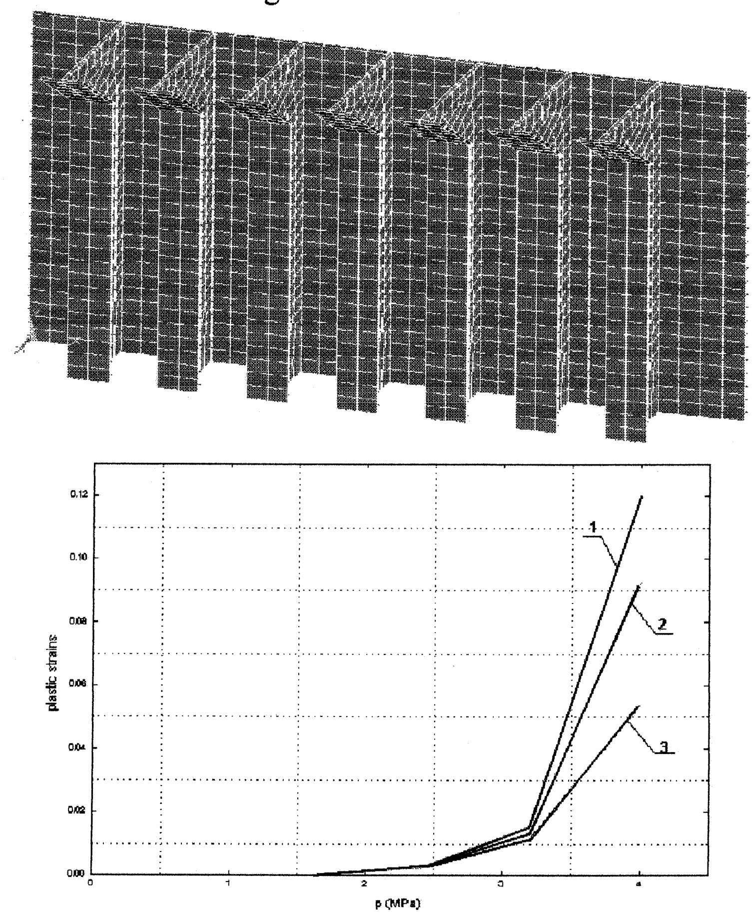

Figure 1. The finite element model of the ice belt grillage panel (a) and the diagram loads – maximal total strain: 1 – σ_u = 400MPa; 2 – σ_u = 450MPa; 3 – σ_u = 500MPa

The numerical investigation was carried out using software for solution of the non-linear strength problem. The result is a significant dependence of plastic deforming parameter on plastic steel hardening parameter.

Dispersion of material properties under the prescribed distribution density for yield stresses $p(\sigma_y)$ could be considered using coefficient $k_\sigma = \sigma_y / \sigma_y^*$. k_σ is a random value with distribution density similar $p(\sigma_y)$, where σ_y^* - standard yield stress, σ_y – random yield stresses. The tensile strength can be expressed as

$$\sigma_u = \sigma_u^* \cdot k_\sigma,$$

where σ^*_u – standard tensile strength corresponding to σ_y.

Thus, the material properties can be described by four values σ_y^*, σ_u^*, ε_0, δ and the distribution density function $p(k_\sigma)$. The strain-stress diagram is assumed to be bilinear. This method allows us to take into account the random nature of steel properties using only one distribution function $p(\sigma_y)$.

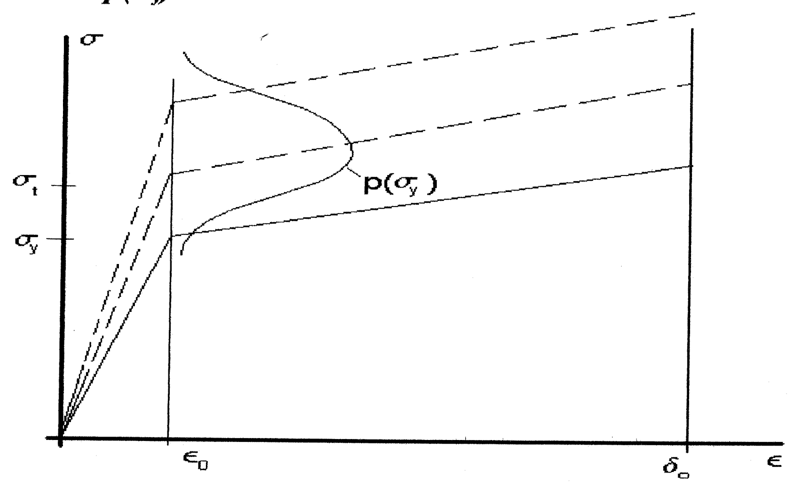

Figure 2. Definition of the probability characters of material properties. $p(\sigma_y)$ – probability distribution function of σ_y.

2.2. Random nature of ice action

This factor is now better understood. There are three basic approaches for investigating the probabilistic parameters of ice loads:

- experimental measurement of ice loads with further statistical data processing;
- stochastic modeling of interaction ice and vessel/offshore structure;
- calculation of ice load parameters based on ice belt structure damage data.

The first approach requires expensive measurement equipment and substantial expeditions cost. There are two directions in this approach which differ in the measurement method. The first one uses special installed pressure gauges as sensors. The gauges are part of shell plating. The RV "Akademik Fedorov" has a similar measurement system [Likhomanov, V. et al; 1995]. The measurement system allows obtaining the statistical parameters of ice loads during full scale trials. The disadvantage of a such systems is high cost of equipment. The second direction uses a structure as part of the measurement system. The measurement devices receive information about the strain parameters in a set of the structure points. The load parameters are recalculated from the signal values in the assumption that parameters of ice loads depend on each other. The disadvantages of such a system are that the results depend on the strength analysis method of a structure and on the assumption about the internal links of load parameters.

The third approach of ice load recalculation based on the damage data allows obtaining real results, which are confirmed by a "full scale test". This approach can be illustrated by the analysis of ice belt structure of the tanker "Samotlor". The damage dimensions are 3.5 m × 2.0 m with the maximal permanent deflection 60 mm. The finite element model similar fig. 1a (400mm spacing, 4.0m frame span, 21.5mm outside plating and the frame profile HP280×11). The calculation results with increasing load allowing us to draw the diagram are shown on fig. 3. The contact area size is close to that of the damage area. The ice pressure – deflection function (fig. 3) can be used for the determination of ice loads (1.1 MPa).

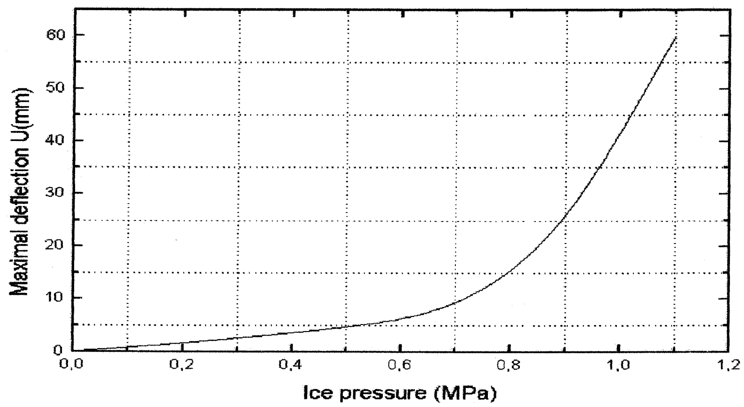

Figure 3. Permanent deflection – ice pressure function

The statistical processing of the results of such calculation could be used for determining the probabilistic laws for the load parameters.

3. FAILURE CRITERIA FOR THE PLASTICALLY DEFORMING STRUCTURES

A failure criterion is an event of the normal operation ability loss by the structure. The failure is the deflection of the structure observed during diving or dock observations in the framework of the posteriori approach. The rules of defection control use the strain criterion indirectly. This means a structure which fails if the maximal permanent strain ε_{max} in some member is more than the limiting strain δ_{lim} $\varepsilon_{max} > \delta_{lim}$. $\delta_{lim} = k_s \cdot \delta$ is the strain value which is part of strain δ_0. k_s=0.2 - 0.5 is a safe coefficient.

The rules of most classification societies for ice belt structure development use an priori approach. The structure failure in this case means the ultimate state of ice belt grillage. The ultimate state is a state of the structure with a sufficient number of plastic hinges for transformation of a structure to mechanism. The ultimate equilibrium theory is based on a range of assumptions the main of which are as follows:

1. The structure material is rigid-plastic or elastic-plastic.
2. The plastic deformation is localized in plastic hinge.

The parameter structure ability in this case is an ultimate load. The mechanism of transformation in the ultimate state should be determined in advance. The real mechanism is assumed as a mechanism with a minimal ultimate load.

A comparison of the ultimate equilibrium theory and a non-linear finite element method (FEM) for the beams of framing was carried out in [Appolonov, E. et al; 1996]. On the other hand FEM give the satisfactory agreement with the experimental measurements [Bond, J. and Kennedy, S.; 1998]. It is worth to compare the predicted behavior of the typical ice belt grillage (fig. 4) using both an analytical method (ultimate equilibrium theory) and numerical calculation (FEM) [Timofeev, O.; 1998].

A comparison of the results can be carried out using a function of ice pressure (arrangement and of contact area are the same) – maximal total strain (elastic and plastic strains) as shown on fig. 5.

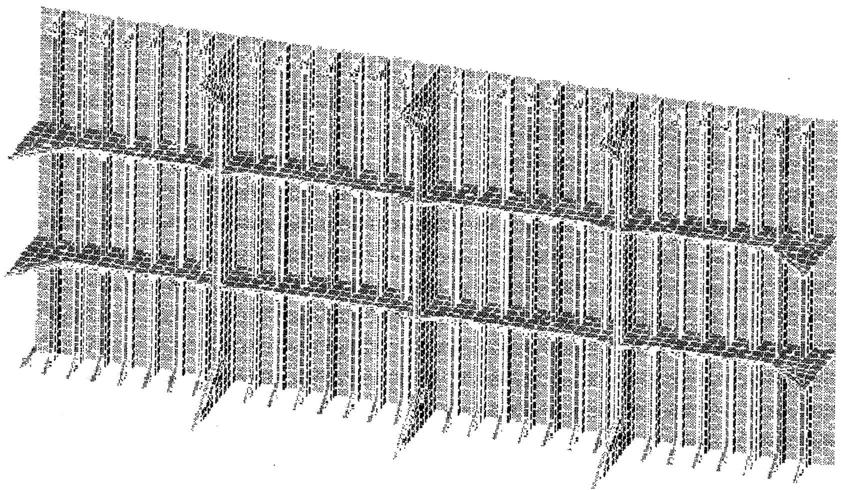

Figure 4. FE model of typical ice belt grillage

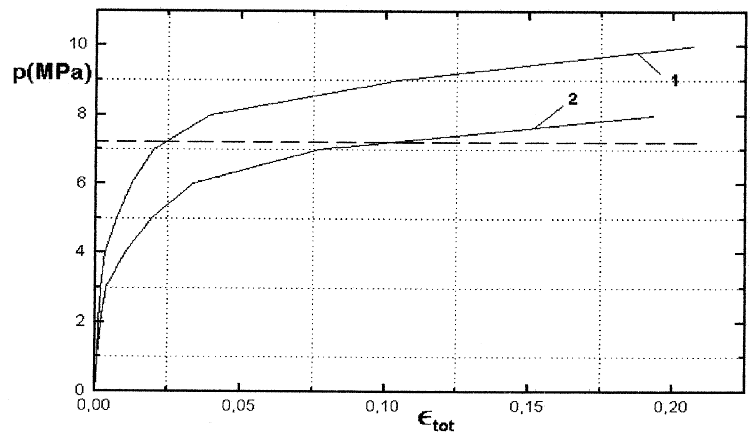

Figure 5. Diagram of ice pressure $\boldsymbol{p}$ (MPa) – maximal total strain ε_{tot} FEA, for fixed boundary conditions (1), for supported boundary condition (2) and ultimate load calculated analytically (dashed line) for the grillage fig. 4

Fig. 5 shows a satisfactory agreement in general between the theory of ultimate equilibrium and more advanced finite element models. A more detailed analysis reveals some contradiction in the assumption about the plastic hinges and the real evolution of plastic zones in framing and plating (fig. 6).

The rules of classification societies for ice belt structure development are based on a comparison of ultimate load and design load and contradict the rules for structure defection control. It is difficult to avoid this contradiction in the framework of the theory of ultimate state because the calculation of deformation is an improperly stipulated procedure under ultimate analysis of a structure. To use the real strain criteria for the structure reliability calculation it is necessary to involve physically and geometrically a non-linear FEM. The proposed failure criterion is equivalence of the maximum total strains and the limiting strain for steel $\varepsilon_{tot} = \delta_0$. This criterion is in good agreement with the rules for a permanent deflection control.

The use of FEM requires additional study, namely:

1. Determination of the optimal finite element type and meshing parameters.

2. Investigation of sensitivity of general deforming parameters to the shape and arrangement of the contact area, shape of pressure distribution over contact area, type of boundary conditions and the hull curvature.

3. Development of a multilevel procedure of the structural strength analysis for the purpose of estimating of reliability and direct strength calculation.

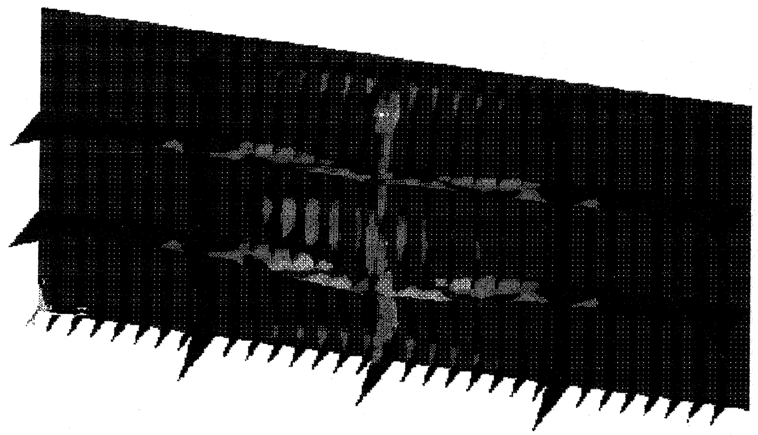

Figure 6. Diagram of plastic strains corresponding to 10 MPa

The first two problems are investigated in [Timofeev, O.; 1998]. The results of these studies allow the following conclusions:

1. An analysis of the strength of ice belt grillage requires to use the shell finite elements with intermediate nodes in the sides. The size of meshing is not less then half of spacing of the main framing. The flanges of frames and brackets can be approximated by non-linear bar elements.

2. The factors of essential influence on the general deforming parameters are arrangement of contact area on grillage and boundary conditions on the grillage edges. The weak influencing factors are the pressure distribution in the contact zone and the grillage curvature. Thus, the list of the loading parameters which are sufficient for the reliability estimation are as follows: the sizes of the rectangular contact area l and b, pressure p uniformly distributed in the contact area and coordinates of the center of the contact area x_0 and y_0 (fig. 7).

There is significant probability of the local damages of structure members: buckling frame webs and plating in the past yield region, plastic bending deformations of flanges and plating. The approach discussed above relates to the whole grillage. It is necessary to develop a more detailed procedure of direct calculations for ice belt structure under the design load. The direct calculation of the ice belt structure can be suggested as a three level procedure.

The first level is a grillage as a whole. The loads and meshing parameters are described above. The second level – a separate frame or a set of frames with a common plating between the web frames and the side stringers (example on the fig. 1). The third level is a separate connection or intersection of the main framing with web frames and side stringers of attached structures.

The development of procedure of the second and third levels demands additional investigation for the determination of optimal meshing taking into account a non-linear effect of large deformation (buckling in the plastic area) and sensitivity of the results to the pressure distribution and boundary conditions. The last two levels use more fine meshing for getting a reliable result of direct calculation.

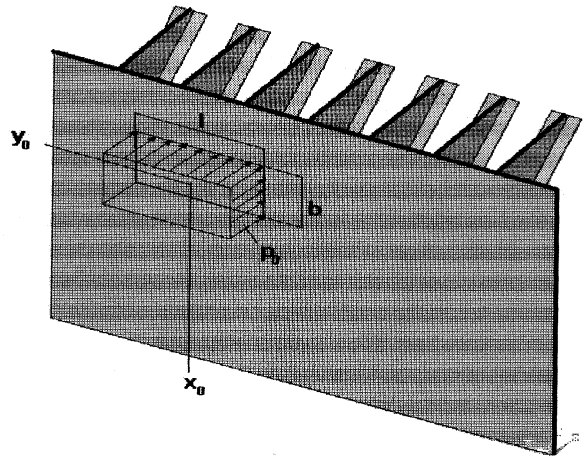

Figure 7. Parameters describing the ice loads on the grillage: $\boldsymbol{l}, \boldsymbol{b}, \boldsymbol{p}, \boldsymbol{x_0}, \boldsymbol{y_0}$

4. PROCEDURE OF THE RELIABILITY ESTIMATION OF THE ICE BELT STRUCTURE

The rules are based on the assumption that the damage occurs because there is a single maximal ice action. Such assumption can be called a single maximal load concept. The reliability estimation algorithm in the framework of this concept was described in [Timofeev O.Ya., 1995]. The input information includes:

1. The structural topology and the size of structural members.
2. The distribution functions for the load parameters which can be presumed an independend random values $p_p(p)$, $p_b(b)$, $p_l(l)$, $p_{x0}(x_0)$ and $p_{y0}(y_0)$ if there is no information on the common distribution function of parameters p, b and l. The first three functions can be obtained using one of three methods described above.
3. The distribution function of material parameter $p(k_\sigma)$ and nominal values σ_y^*, σ_u^*, ε_0 and δ_0.

The algorithm consists of two stages:

1. The development of the structural state surface based on the chosen failure criteria in coordinates of load parameters p, b, l, x_0, y_0 and material parameter k_σ. The structural state surface is a set of points in space $(p, b, l, x_0, y_0, k_\sigma)$ for which the structure fails. The failure state surface can be described by function $\Phi(p, b, l, x_0, y_0, k_\sigma)$.
2. The calculation of the reliability of structure

$$R = \int_\Omega p_p(p) \cdot p_b(b) \cdot p_l(l) \cdot p_{x_0}(x_o) \cdot p_{y_0}(y_0) \cdot p(k_\sigma) d\Omega$$

Ω is the area of permissible states of a structure bound by function $\Phi(p, b, l, x_0, y_0, k_\sigma)$. An example of calculation of reliability of the ice belt structure of an offshore platform can be obtained in [Timofeev O., Klenov A., 1996].

The investigation of plastic deforming of metals and metal structures which was made in machinery industry show that permanent plastic deformation are cumulated. The first proposal to consider the cummulation of plastic deformation for ice belt structures was in [Belenky L.M., 1983]. Belenky L.M. explained the process of the cumulation of plastic deformation by partial or complete relaxation of the fields of residual stresses. Note the following factors causing the cumulation of permanent plastic deformation:

1. Changing of material properties under cyclic plastic deformation (Baushinger effect) which could be taken into account using the kinematics theory of hardening. The numerical investigation of influence of Baushinger effect carried out in [Timofeev O.Ya., Nikolaev P.M., 1987].
2. Changing (redistribution) of the residual stress field after the repeat loading if the position of the contact area also changes. This cumulation mechanism was called redistributive and was investigated in [Timofeev O., 1996]. The redistributive mechanism predicts increasing of permanent deflection several-folds. There is also another loading (general hull bending) which redistributes the residual stresses.
3. Relaxation of residual stresses causing the structure vibration. The residual stresses can be twice reduced for 1-2 sec if the frequency of oscillation is close to the structure natural frequency [Gatovsky K.M., Karkhin B.A., 1980].

The investigation of the contribution of the aforementioned cumulation factors is a problem for the near future.

Approach to the structure reliability estimation taking into account the process of permanent deformation cumulation. The prediction of the structure state taking into account the cumulation of permanent deformation is possible using the theory of Markov process [Bogdanoff J., Kozin F., 1985]. To use the theory of the Markov process it is necessary to formalize the Markov property of the object. The formalization procedure must make the structural state independent of the previous history of loading. The structure can be described with sufficient accuracy in the terms of finite element parameters (permanent deflections and residual stresses) after any cycle of loading-unloading. Another event which demands formalization is transition from one state to another. In case of ice interaction such transition is one of the thee events:

1. Ice loading is a five component stochastic process, which leads to the redistribution of residual stresses and increasing permanent deflection. Using a model of the material with kinematics hardening includes a Baushinger effect.
2. Loading of the grillage during general hull bending. This leads to the redistribution of the residual stresses.
3. Relaxation of the residual stresses, which can be taken into account in the coefficient of relaxation [Belenky L.M.]. The coefficient of relaxation depends on duration and frequency of vibration action.

CONCLUSION AND ACKNOWLEDGEMENTS

The paper contains a description of the posteriori and priori approaches to the evaluation of reliability of ice belt structures. The priori approach can be realized both in the framework of the single maximum loading concept and taking into account the cumulation of the permanent deflections. The second approach allows us to predict not only the probability of failure but the durability of the structure as well.

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