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IMPROVEMENT OF TRAWLER HULL STRUCTURE UNDER CONDITION OF ENSURING FATIGUE STRENGTH

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The structure of the hull of the project 1288 trawler in a region of fore hold was improved to ensure fatigue strength of joints of the intersection of main frames with the double bottom. To this end, a study of the fatigue strength of these joints was carried out for the original side structure and two versions of its modernization.

Values of internal forces at the points of initiation of fatigue cracks in the compartment have been determined for three design versions of the side. It was found that the greatest forces act in the middle of the fore half of the compartment.

Calculations of parameters of the long-term distribution of magnitudes of ranges of total equivalent operating stresses according to the Weibull law in the points of occurrence of fatigue cracks for different design versions of the side grillage have been performed. These parameters were determined for the middle of the fore hold of the vessel and for the areas with maximum values of bending moment ranges. The calculations were performed with and without accounting of effect of corrosion.

Values of total fatigue damage and durability of the studied joints were determined. Calculations were carried out by nominal stress method, hot spot stress method, and experimental and theoretical method.

It was shown that in order to ensure fatigue strength of the joint under consideration, it is necessary to extend the intermediate frames of the original version of the side structure to the level of the tank top fixing them to the last one. It is also necessary to attach a cargo platform to the side thus reducing the frame span. As a result, the level of fatigue damage over 25 years of operation will decrease by about 3.5 times.

As it was found, approximate consideration of the slamming effect does not significantly increase the amount of fatigue damage of the joint.

The results of the development of recommendations for modernization of the side structure can be implemented both on ships of the 1288 project and on other ships with a transverse side framing system

Keywords: trawler, side structure, structural joint, stress-strain state, stress concentration, fatigue strength

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1. Introduction

For efficient operation of ships, it is necessary to minimize their mass on the one hand and ensure strength and sufficient reliability of its structure on the other hand. It is also necessary to minimize the number of ship repairs in operation.

To accomplish this task, it is necessary to calculate the local and overall fatigue strength of the ship structures at the design stage. Also, it is necessary to analyze cyclic strength and, if necessary, modernize the structures of the ships in service.

Big freezer trawlers of project 1288 with dimensions of 106.9×16×10.2 m are currently operating in a number of countries. Operation of trawlers has shown that fatigue cracks appear in structural joints connecting main frames with a double bottom for several years. These cracks must be eliminated in regular repairs. It is obvious that cracks can occur in the same places on other vessels with a transverse side framing system.

The results of working out recommendations for modernizing the side structure to extend its fatigue life can be implemented both on vessels of the 1288 project and on others vessels with a transverse side framing system.

2. Literature review and problem statement

Work [1] reports a study of fatigue strength of the fishing ship structures. Structures of the upper deck which are subject mainly to the loads caused by the hull girder bending are considered in this work. The shorter the ship the smaller intensity of such loads. This explains the fact that the cyclic strength of all upper deck structures considered in [1] was ensured taking into account the fact that the length of fishing ships usually does not exceed 100 m. Fatigue strength of the structures subject to predominantly variable local loads from the pressure of the cargo and outside water has not been studied.

Work [2] should be pointed out, in which fatigue strength of some structural welded joints of the bulk carrier was investigated (length between perpendiculars L_{pp}=179.37 m). Fatigue calculations were performed in this study according to the recommendations of the International Association of Classification Societies (IACS) [3] and using the Rules of Bureau Veritas, Germanischer Lloyd, Lloyd's Register. Magnitudes of ranges of total operating stresses acted on the structural joints were determined on the basis of the listed regulations. For example, a simplified approach was applied in [2] to calculate stress ranges and their long-term distribution in structures. The same approach was used in report [4]. Besides, this report presents results of fatigue calculations based on the measurement of vessel movement parameters and wave characteristics. These data were collected over a year of operation. Next, long-term distribution of stresses acting in the joint and, accordingly, annual fatigue damage and the structure durability were determined on the basis of these data.

Report [4] considered the joint in the location of the hatch cut in a bulk carrier with a structure modernized to extend its fatigue life. Values of durability and fatigue damage of the modernized structure were compared with the same values for the original structure. As a result, according to various calculations, 1.82 or 2.76 times increase in cyclic strength of the structure was achieved. Thus, a possibility of upgrading individual structures of the constructed vessel in order to ensure fatigue strength was shown. At the same time, according to the simplified approach, the calculation of external variable loads acting on the joint makes it possible to obtain conservative results in comparison with the measured data.

Fatigue strength of the large ship side structure was also studied in [4]. The side was built using the longitudinal side framing system.

A simplified approach to determining the long-term distribution of stress ranges was also used in [5] when analyzing fatigue strength of ties of the overall cross-section of the gas carrier hull (L_{pp}=216.1 m) in the midship section. Analysis of cyclic strength was performed for cross-sections at the junction of longitudinal ties with the transverse frame and bulkhead. Fatigue calculations were carried out in accordance with recommendations of Det Norske Veritas (DNV) taking into account the fact that structural joints are in a corrosive environment for a part of the vessel's operation time.

It is shown in [4, 5] that the ship side structures subject to variable external pressures from the action of outside water are critical areas from the point of view of ensuring fatigue life. The results presented in [4, 5] refer to double sides built according to using the longitudinal side framing system. Thus, they do not make it possible to judge the cyclic strength of the joint between the frame and the double bottom of ships with a transverse side framing system.

Fatigue calculation of the structural joint of the joint of the longitudinal main deck stiffener of the barge (L_{pp}=73.2 m) with the beam was performed in [6] according to the IACS recommendations [3]. In this case, the long-term distribution of loads on the joint was determined using the previously mentioned simplified procedure. The result of this calculation was compared with the result of the fatigue calculation obtained by determining the long-term distribution of loads on the joint using the spectral method. It was shown that a simplified approach to calculating the variable external loads acting on the ship hull structures enables obtaining conservative results in comparison with the more detailed spectral method.

The spectral method was also used in [7] when conducting fatigue calculation of the joint of the intersection of the longitudinal stiffener of the side and the frame of a container ship (L_{pp}=281 m). The results of this calculation were compared with the assessment of this joint durability by determining the specific fatigue damage of the joint over a 20-minute interval taking into account the probability of the vessel meeting different wave conditions during its operation in the North Atlantic regions.

It was shown in [6, 7] that the application of the spectral method to determine the long-term distribution of loads acting on the ship hull joints substantially complicates calculations. For comparative analysis of fatigue of initial and modernized versions of the investigated ship structures, it is sufficient to apply a simplified approach to the determination of external loads.

A study of fatigue strength of intersection of the longitudinal upper deck stiffener and the web beam of the tanker (L_{pp}=236 m) was carried out in [8]. The long-term distribution of nominal stresses in the joint was determined using general IACS Rules and a computer program additionally implemented on the basis of the linear strip theory. It was shown in this work that the condition for ensuring fatigue strength can serve as the main criterion when choosing the dimensions of the ship's hull ties. It was also shown that the durability of the hull elements of ships designed according to the «old» Rules without taking into account the present-day criteria of fatigue strength can be significantly less than the design life of the ship.

A study of the overall fatigue strength of a tanker taking into account nonlinearity of accumulation of fatigue damage because of gradual reduction of the mid-frame cross-section caused by corrosive wear was carried out in [9]. Two approaches were used there to take into account corrosive wear: a decrease in design thicknesses when calculating effective stresses and taking into account a gradual decrease in thicknesses when calculating fatigue damage of the structures using a nonlinear relationship. Norms of the Russian Maritime Register of Shipping also indicate that corrosive wear should be taken into account when calculating the stresses acting in ties. In this case, the design dimensions of structures are reduced by the amount of corrosion allowance.

Results of studies of fatigue strength of tanker structures carried out according to the recommendations of DNV (2003) and IIW (International Institute of Welding, 2009) taking into account corrosive wear at various parameters of the finite element mesh density were presented in [10]. The effect of corrosion was taken into account approximately, by multiplying the fatigue damage obtained for operating conditions in the air by the coefficient of corrosion effect on the cyclic strength. This approach differs from that used in [9]. The issue of expediency of applying one or another approach to assessing the fatigue life of structures in a corrosive environment requires additional studies.

A comparative analysis of values of fatigue damage to the structural joint of the upper deck of a dry cargo ship (L_{pp}=139 m) calculated on the basis of various methods was carried out in [11]. The joint under study [11] is similar to the joint between the frame and the double bottom. Similar calculations were performed in [12] for the hot spot in the ship superstructure.

It should be noted that the authors of these works recommend the strain-life approach to calculating fatigue strength for practical application. However, this approach is usually used only for calculations in the low-cycle region. For the region of medium and high fatigue life, it is customary to use force methods in the design practice.

Systematizing the results of the reviewed works, it can be noted that large-tonnage vessels (tankers, bulk carriers, and container ships) are considered in most of the studies devoted to determining the fatigue strength of the ship hull structures. This is explained by the fact that structures of such ships experience significant variable forces from the overall hull girder bending. Such vessels are usually built using the longitudinal side framing system.

There are practically no publications devoted to studies of the cyclic strength of trawler vessels. At the same time, 111 vessels were built only according to the 1288 project. Also, there are practically no publications devoted to the study of fatigue strength of vessel side structures built using the transverse side framing system.

Fictitious notch rounding and hot spot stress approaches are used in research works for fatigue analysis of welded structures. These approaches are based on the use of finite element analysis. The nominal stress approach is used less commonly.

Reduction of design thickness of ties is the simplest and most conservative way to take into account the effect of corrosive wear when analyzing cyclic strength of the ship hull structures and calculating the stresses acting in them.

It can be seen from [2–6, 8, 9] that a simplified approach to assessing external variable loads acting on ship structures is widely used in practice. It makes it possible to reduce greatly the number of calculations in comparison with other approaches to assessing the long-term distribution of external loads. The results of assessing the durability of structural joints based on this approach were 1.5–2 times less. Thus, to obtain more accurate quantitative results for durability, the spectral method can be used for determining external loads. Also, the results of measurements obtained on prototype ships during a certain period of their operation can be used.

Based on the presented analysis, it can be concluded that it is advisable to conduct a study of fatigue strength of the joint of main frames with the double bottom of a trawler vessel with a transverse side framing system.

It is also advisable to develop versions of modernizing such a structure in order to ensure a sufficient level of fatigue strength.

3. The aim and objectives of the study

The study objective implied the improvement of the hull structure in the ships of project 1288 to ensure the necessary level of fatigue strength according to the recommendations of the International Association of Classification Societies.

To achieve the objective, the following tasks were set:

– determine the magnitude of the range of operational loads acting on the ship compartment, and, accordingly, the magnitude of the range of bending moments from bending of the grillage and the beam at the points of fatigue cracks initiation («hot spots») along the compartment for the original and modernized design versions;

– determine parameters of the long-term distribution of ranges of equivalent operating stresses in «hot spots» with and without corrosive wear in the middle of the compartment and sections where maximum internal forces were acting;

– determine total fatigue damage to the studied joints during the service life of the vessel and their durability.

4. The study materials and methods

4. 1. Description of the problem

Fatigue cracks in the hull of an operating vessel appeared in the fore hold No. 1. The hold location is shown in Fig. 1. Cracks appeared in joints of the junction of main frames with a double bottom, at the endpoint of the bilge knee on the frame (Fig. 2).

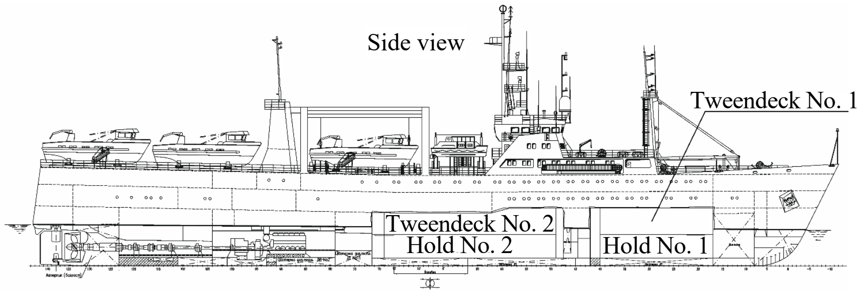

Fig. 1. General layout of the vessel. Side view


a

b

Fig. 2. Fatigue cracks in structural joints: *a* — position of «hot spots» in the vessel fore hold; *b* — crack in the area of transition from the base metal to the weld

4. 2. The procedure of calculating the cyclic strength of a structural joint

Fatigue analysis of the abovementioned structural joint was carried out using the IACS recommendations [3]. In accordance with these recommendations, fatigue analysis of structural joints was performed according to the linear hypothesis of summation of fatigue damages which is given in the following form [13] for a continuous long-term stress distribution:

$$D = N^{*} \int\limits_{(\Delta\sigma_n)_{\min}}^{(\Delta\sigma_n)_{\max}} \frac{p(\Delta\sigma_n)}{N(\Delta\sigma_n)} \mathrm{d}(\Delta\sigma_n), \tag{1}$$

where $\Delta\sigma_n$ is the range of the nominal stress cycle; $p(\Delta\sigma_n)$ is the probability distribution of $\Delta\sigma_n$; $N(\Delta\sigma_n)$ is the dependence of the number of cycles until fatigue failure occurs (or appearance of a fatigue crack of a certain length) on the value of $\Delta\sigma_n$; $(\Delta\sigma_n)_{\min}$, $(\Delta\sigma_n)_{\max}$ are minimum and maximum ranges of nominal stresses in the range of loading of the object under study; N^* is the number of loading cycles during the service life (calculated according to [3]).

It should be noted that the IACS recommendations [3] contain a slightly modified relationship (1) which takes into account the shape of fatigue curves and long-term distribution of nominal stress ranges according to the two-parameter Weibull's law.

According to this law, the probability distribution function of stress is expressed by the following relationship:

$$p(\Delta\sigma_n) = k_W\left(\Delta\sigma_n^{k_W-1}/a_\sigma^{k_W}\right)e^{-(\Delta\sigma_n/a_\sigma)^{k_W}}, \tag{2}$$

where k_w is the shape parameter; a_σ is the scale parameter of the distribution.

As indicated in [3], parameters k_w, a_σ can be determined using a simplified approach according to which:

$$k_W = 1.1 - 0.35\frac{L-100}{300}, \tag{3}$$

$$a_\sigma = \frac{\Delta\sigma^\Sigma}{\left(\ln N_{ch}\right)^{1/k_W}}, \tag{4}$$

where L is the vessel length, m; $\Delta\sigma^\Sigma$ is the magnitude of the range of overall nominal operating stresses with a probability of their occurrence $1/N_{ch}$, Pa.

The $\Delta\sigma^\Sigma$ value was calculated according to the strength standards of the Russian Maritime Register of Shipping (RMRS) [14]. A critical value of the damage level D was taken equal to one and the value of $1/N_{ch}$ was equal to 10^{-3}.

For fatigue calculations, two design conditions were considered: «loaded condition» and «ballast condition». The share of the time spent by the vessel in «loaded condition» is 75 % and 25 % in «ballast condition» (for cargo ships in accordance with [3]).

Thus, the total fatigue damage of the joint during the vessel service life D_{tot} and its cyclic life T_f can be determined using the following dependences [3, 13]:

$$D_{tot} = D_1 + D_2, \tag{5}$$

$$T_f = T_d / D_{tot}, \tag{6}$$

where D_1 and D_2 are fatigue damages of the structural joint during the stay in «loaded condition» and «ballast condition», respectively; T_d is the design service life of the vessel.

Only local loads were taken into account for the considered joint of the intersection of the frame with the double bottom, namely, overall pressures from the action of waves and cargo. Variable loads on the vessel hull were determined according to a simplified approach in accordance with which it is necessary to determine variable pressures on the hull with operational probability according to the register norms.

Three versions of the structure of the compartment side grillage were considered:

1) with intermediate frames brought up to the lower longitudinal edge of the side (original structure version);
2) with intermediate frames extended to the tank top;
3) with intermediate frames extended to the tank top and a reinforced side girder in the middle of the hold height.

The last two versions were proposed as modernization of the side grillage structure in the cargo hold No. 1 to ensure fatigue strength of the joints of the intersection of the main frames with the double bottom.

Internal forces in the ship hull structures were calculated on the basis of the finite element method. Solidworks and Salome-Meca software packages were used for finite element analysis and development of computer models.

Parameters of long-term distribution of operational loads in «hot spots» were determined on the basis of (3), (4). At the same time, it should be noted that the value of total operational nominal stresses $\Delta\sigma^\Sigma$ in the «hot spots» is effective. It enables taking into account simultaneous action of local loads and forces from the hull girder bending.

Such stresses were calculated using the following dependence:

$$\Delta\sigma^\Sigma = \sqrt{\sum_{j=1}^{3}\Delta\sigma_j^2 + 2\sum_{j=3}^{3}\sum_{v=1}^{3}\rho_{jv}\Delta\sigma_j\Delta\sigma_v}, \tag{7}$$

where $\Delta\sigma_j$, $\Delta\sigma_v$ are the components of ranges of alternating stresses from the hull girder bending, the grillage and beam bending; $\rho_{jv}\approx\pm 0.5$ is coefficient of correlation of the considered stress components (the sign «+» or «–» here depends on the location of the considered «hot spot» in the grillage).

The influence of average cycle stresses on fatigue strength of joints was not taken into account.

Values of the stress components from bending of the grillage $\Delta\sigma_2$ and the beam $\Delta\sigma_3$ when using the rod model of the compartment are determined as follows:

$$\Delta\sigma_{2,3} = \frac{\Delta M_{g,b}\cdot z_f}{I}, \tag{8}$$

where ΔM_g, ΔM_b are magnitudes of the bending moment ranges at the «hot spot» from bending of the grillage and the beam, respectively; I is the moment of inertia of the cross-sectional area of the beam; Z_f is the distance from the neutral axis of the beam to the flange.

According to [14, 15], magnitudes of the stress ranges $\Delta\sigma_2$, $\Delta\sigma_3$, and the equivalent $\Delta\sigma^\Sigma$ were calculated taking into account and without taking into account decrease in the cross-section of beams caused by corrosive wear by the end of the design service life of the vessel (25 years).

4. 3. Methods of calculating the fatigue strength of the welded joint under study

The nominal stress approach, the hot spot stress approach, and the experimental and theoretical method (ETM) were used to assess fatigue strength. The first two of these methods are widespread in the world practice and are presented in regulatory documents of leading classification societies and international institutions.

The design model of the studied joint of the frame with the double bottom structures is shown in Fig. 3.

The nominal stress approach assumes typification of the studied area of the ship's hull where fatigue damage is possible in accordance with the classification presented in normative documents for calculating the fatigue strength of welded joints. The method is presented, for example, in recommendations of IACS [3], DNV-GL [16], International Institute of Welding (IIW) [17]. After typification of critical areas, a corresponding S-N fatigue curve is selected for each such area in accordance with the above regulatory documents.

A digital code FAT (fatigue class) is assigned to a welded joint depending on its appearance, loading method, manufacturing features, etc. This code corresponds to the structure endurance limit at $2 \cdot 10^6$ loading cycles.

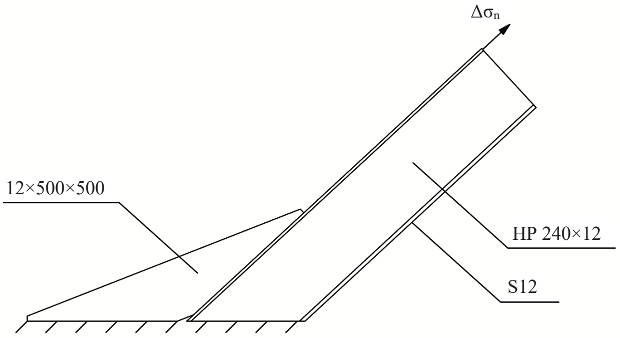

Fig. 3. Plane model of the joint under study

The sloping parts of the S-N curves are described by the equation:

$$\lg N = \lg C - m \cdot \lg \Delta\sigma_n, \qquad (9)$$

where N is the number of cycles before the crack initiation; $\Delta\sigma_n$ is the range of nominal stresses in the cycle; lg$C$, m are the constants defined for alphanumeric code in the corresponding regulatory document.

According to the classification presented in [16, 17], the *S-N* curve of class 63 corresponds to the joint under study.

The hot spot stress method described in [3, 16–18] involves the determination of design stresses in a welded joint using special techniques based on the use of the finite element method or experimental methods. These stresses include the effects of stress macro concentration and exclude the stress build-up determined by the presence of the welded seam. It is assumed that the effect of the presence of a welded seam on the fatigue strength of a structural joint according to this method has already been taken into account in the *S-N* curves of a certain fatigue class used in the durability calculation.

Structural stresses at the hot spot $\Delta\sigma_{hs}$ are determined by extrapolating stresses from special points. The position of these points is regulated by relevant recommendations. Extrapolation can be linear or quadratic, two- or three-point, respectively.

The stress concentration factor at the «hot spot» for the joint under consideration can be approximately determined according to the data in [16], K_{hs}=1.43. Parameters of the *S-N* curve for fatigue calculations by the hot spot stress approach are presented in [16] (the curve of class 90 or *D*).

The experimental and theoretical method (ETM) of calculation of fatigue in the ship hull structures was developed at the Admiral Makarov National University of Shipbuilding [19]. The initial object in this method is not the joint as a whole but individual centers of stress concentration occurring in it. The weakest of them is determined by the fatigue strength of the joint and, accordingly, the entire structure. The main element in this procedure of durability assessment is the fatigue curve of the stress concentration zone.

The fatigue curve constructed by the experimental and theoretical method for the case of loading with a constant range shown in Fig. 4, consists of 3 sections. It is constructed on the basis of criteria dependences of material fatigue using experimental data of fatigue tests of full-scale or semi-full-scale models at a given level of nominal stresses. The mentioned fatigue curve is presented in a semi-logarithmic coordinate system: n=log$N$ and $\bar{\sigma}_n = \Delta\sigma_n / \Delta\sigma_{n0}$. The index «0» at $\Delta\sigma_{n0}$ and n_0 means that these values refer to experimental data. $\Delta\sigma_{n0}$ is the range of nominal stresses taking place in the model during its fatigue test that established a number of cycles N_0 until a 1…2 mm long crack appeared. To construct section II of the curve, the strain-life criterion of material fatigue proposed by Langer is used and the Heywood stress-life criterion is used to construct section III. In this case, «binding» of a typical stress concentration zone to the results of cyclic tests occurs in section II at a point with coordinate n_0.

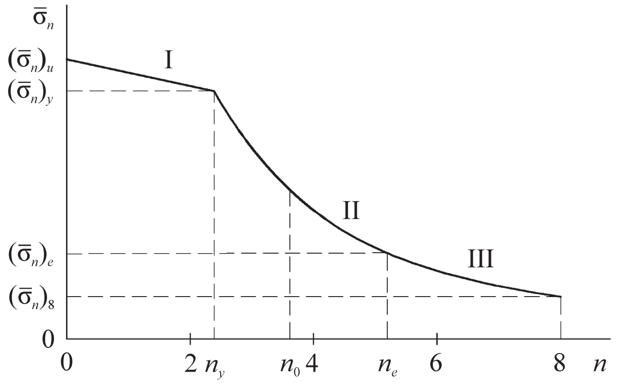

Fig. 4. Fatigue curve obtained according to the experimental and theoretical method

When a load of stochastic nature is acting on the structural joints which is typical for ships, a modified version of the ETM should be used. Its dependences are presented in [20].

Performing fatigue calculations using this method involves determining the theoretical stress concentration factors for the structural joint under study and for the joint that was fatigue tested in laboratory conditions, that is, K_t and K_{t0}, respectively.

5. The results obtained in the studies of fatigue strength of the ship hull structures

5. 1. The results of determining the magnitude of bending moment range from the grillage and beam bending at the points of fatigue cracks initiation

For each of the three versions of the side embodiment, a finite element model of the compartment was developed based on the beam idealization to calculate the bending moments determined by the grillage bending.

The finite element model for the original design version is shown in Fig. 5 with applied overall loads (ranges of values) caused by the action of the cargo and seawater. Finite elements of the first order were used for its construction. The total number of elements is 3255.

Distribution of ranges of bending moments from the grillage bending ΔM_g at the «hot spot» along the compartment length for different versions of the side structure is shown in Fig. 6 (design condition: «fully loaded»).

Calculation of fatigue strength was carried out for sections with the highest bending moment from the grillage bending in the area of frames 24–25 and in the middle of the compartment.

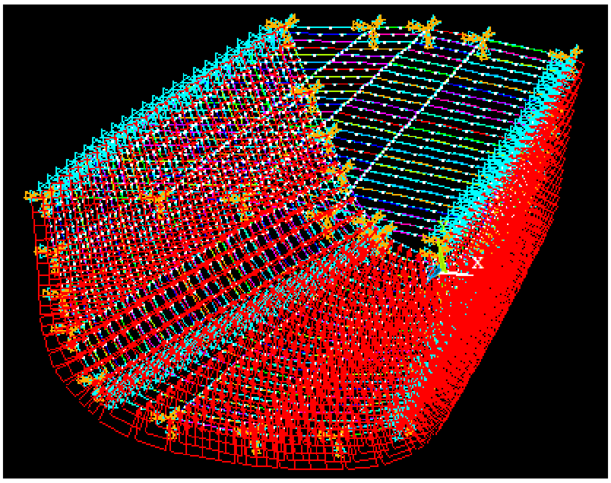

Fig. 5. Finite-element model of the compartment with applied loads for the original version of the side structure

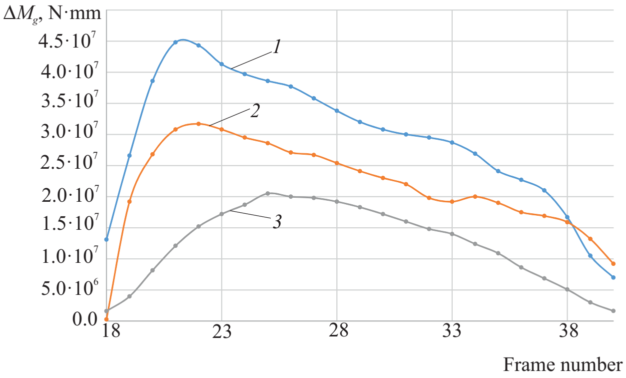

Fig. 6. Distribution (along the length of the cargo hold No. 1) of magnitudes of ranges of bending moments at the «hot spot» caused by the grillage bending: 1, 2, 3 are versions of the side design according to Section 4. 2

For the «ballast condition», values of bending moments in the «hot spots» are presented in Table 1 for the indicated areas of the compartment under study.

Table 1

Magnitudes of the range of bending moments from the grillage bending at «hot spots» for all versions of the side structure («ballast condition»)

Number of the side structure version	ΔM_g, N·mm	
	The greatest, in the region of frames 24–25	In the middle of the compartment, in the region of frame 29
1	$1.79 \cdot 10^7$	$1.58 \cdot 10^7$
2	$1.33 \cdot 10^7$	$7.86 \cdot 10^6$
3	–	–

When calculating the magnitudes of ranges of bending moments ΔM_b from bending of the beam at the «hot spot», the frame in the fore hold was considered as a multi-span beam fixed at the end points and rested on elastic supports. Longitudinal side stiffeners act as elastic supports.

In the case of the original version of the side structure, the intermediate frames which did not reach the double bottom were included in the cross-section of the beam. In the design scheme, the presence of a bilge knee was taken into account by a decrease in the beam length according to [14].

The results of calculating the range of bending moments ΔM_b from the beam bending at the «hot spot» for various versions of the side structure and «fully loaded condition» and «ballast condition» are presented in Table 2.

Table 2

Results of calculating the range of bending moments at «hot spots» from the beam bending

Number of the side structure version	ΔM_b, N·mm	
	«fully loaded condition»	«ballast condition»
1	17044	10821
2	7665.2	4738.2
3	7551.3	4738.2

The numbers of versions of the side embodiment given in Tables 1, 2 correspond to the numbers of versions of the design of the compartment side grillage presented in Section 4. 2.

5. 2. The results of determining parameters of the long-term distribution of ranges of operating loads at «hot spots»

Values of the scale parameter of long-term distribution a_σ of ranges of nominal equivalent operating stresses at «hot spots» according to Weibull's law (2) for various versions of the design of the side grillage are presented in Tables 3, 4.

Table 3

Values of the scale parameter of distribution of the nominal equivalent operating stress ranges at the «hot spot» according to Weibull's law a_σ, MPa («full loaded condition»)

Version of the side structure	Maximum values in the region of frames 24–25		Values in the middle of compartment in the region of frame 29	
	Without accounting for the corrosive wear	With accounting the corrosive wear	Without accounting for the corrosive wear	With accounting the corrosive wear
1	19.80	23.50	14.333	17.014
2	16.85	19.86	14.752	17.384
3	13.73	16.26	12.64	14.97

Table 4

Values of the parameter of the scale of distribution of nominal equivalent operational stresses at the «hot spot» according to Weibull's law a_σ, MPa («ballast» condition)

Version of the side structure	Maximum values in the region of frames 24–25		Values in the middle of compartment in the region of frame 29	
	Without accounting for the corrosive wear	With accounting the corrosive wear	Without accounting for the corrosive wear	With accounting the corrosive wear
1	8.39	9.96	7.79	9.24
2	8.38	9.87	5.85	6.90
3	–	–	–	–

The calculations were performed with and without regard to corrosive wear over 25 years of operation at $k_w=1.077$ and $N_x=103$ according to the RMRS standards [14]. The conditions under consideration: «fully loaded condition» and «ballast condition».

5.3. The results of calculation of the total fatigue damage of the studied joints and their durability

When performing fatigue calculations of welded joints by the experimental and theoretical method to determine the point of «binding» of the fatigue curve to the experimental data, the detail shown in the diagram of Fig. 7 was selected. Laboratory cyclic tests were performed for the models of such detail. The results of these tests are presented in [21].

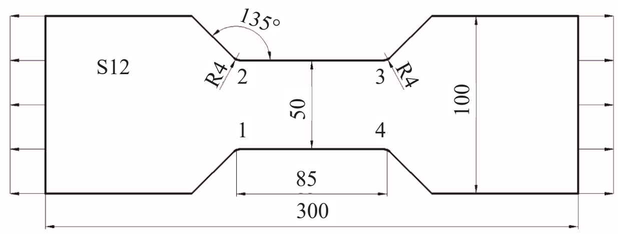

Fig. 7. Scheme of the detail for which a series of fatigue tests were performed

Based on the results of finite element analysis, the theoretical stress concentration factor for the detail which was tested for fatigue in laboratory conditions was $K_{t0}=5.128$. The joint material was the steel of 09G2 grade. According to the test results on flat specimens, the steel characteristics were as follows: yield stress $\sigma_{s0}=340$ MPa; ultimate tensile strength $\sigma_u=460$ MPa.

The theoretical stress concentration factor for the joint under study (Fig. 3) was determined using finite element analysis and the procedure described in [13].

According to the data of [22], the slamming effect on fatigue strength of the junction between the frame and the double bottom structures was taken into account. In accordance with the latter, a simplified calculation of fatigue damage of the joint from wave loads taking into account superimposed high-frequency stresses, includes the following steps:

1. Assessment of maximum increase in the range of wave stresses when the high-frequency component is applied, obtained from measurements or results of analysis of such stresses based on calculated pressures from slamming determined in accordance with the Rules.
2. Increase in the cumulative distribution of the wave stress ranges through multiplying by the coefficient obtained in p. 1.
3. Application of the Miner linear damage rule.

The slamming pressures were calculated according to the RMRS Rules [15] for the «ballast loading condition». The slamming pressures were not taken into account for the «fully loaded condition». This is determined by the fact that slamming usually occurs in vessels with a small forward draught (when sailing upwave with ballast or an incomplete load) [23].

Thus, the slamming influence coefficient was $K_{sl}=1.202$. Multiplication of the cumulative distribution of the nominal stress ranges in the «hot spot» for the «ballast condition» by this coefficient K_{sl} makes it possible to take into account the slamming effect on fatigue strength of the joint under consideration with a margin towards overestimation. The previously indicated value of K_{sl} was taken approximately when calculating the slamming effect for all three cases of the side structure versions.

Values of fatigue damage D_1 and D_2 of the ship hull under study in the region of frames 24–25 and frame 29 are presented in Table 5. When calculating D_2 for the «ballast condition», the slamming effect was taken into account. The row numbers in the table correspond to various side grillage structures presented in Section 4. 2.

When calculating the fatigue damage of the joint under study applying the experimental and theoretical method, the procedures presented in [13] were used.

For version 3 of the side embodiment, in «ballast condition», fatigue damage D_2 was not calculated. As shown for the other two versions of the side structure, this design condition does not significantly contribute to the cumulative fatigue damage D_{tot}.

Values of the total fatigue damage D_{tot} as well as the values of the predicted service life T_f of the welded joints of the intersection of frames with the double bottom structures are presented in Tables 6, 7.

Table 5

Values of the fatigue joint damage D_1 and D_2 in the region of frames 24–25 without and with taking into account corrosive wear over 25 years of operation

Number of the side embodiment version	Nominal stress approach		Hot spot stress approach		Experimental and theoretical method	
	D_1	D_2	D_1	D_2	D_1	D_2
1	4.13/7.10	0.13/0.26	4.10/7.08	0.11/0.23	5.02/9.70	0.08/0.19
2	2.44/4.17	0/13/0.25	2.41/4.14	0.11/0.23	2.64/5.08	0.08/0.18
3	1.22/2.17	–	1.18/2.13	–	1.12/2.28	–

Table 6

Values of the total fatigue damage D_{tot} and fatigue life T_f of the joint in the region of frames 24–25 without and with taking into account corrosive wear over 25 years

Number of the side embodiment version	Nominal stress approach		Hot spot stress approach		Experimental and theoretical method	
	D_{tot}	T_f, years	D_{tot}	T_f, years	D_{tot}	T_f, years
1	4.26/7.36	5.87/3.4	4.21/7.31	5.94/3.42	5.10/9.89	4.9/2.53
2	2.57/4.42	9.73/5.66	2.52/4.37	9.92/5.72	2.72/5.26	9.19/4.75
3	1.22/2.17	20.49/11.52	1.18/2.13	21.18/11.74	1.12/2.28	22.32/10.96

Table 7

Values of total fatigue damage D_{tot} and fatigue life T_f of the joint in the region of frame 29 without and with taking into account corrosive wear over 25 years

Number of the side embodiment version	Nominal stress approach		Hot spot stress approach		Experimental and theoretical method	
	D_{tot}	T_f, years	D_{tot}	T_f, years	D_{tot}	T_f, years
1	1.51/2.71	16.56/9.23	1.46/2.65	17.2/9.43	1.39/2.87	17.99/8.71.
2	1.59/2.76	15.72/9.06	1.54/2.72	16.23/9.19	1.53/3.02	16.34/8.28
3	0.91/1.64	27.42/15.24	0.87/1.60	28.74/15.63	0.77/1.61	32.47/15.53

The results presented in Tables 6, 7 were obtained for the regions of the fore hold where maximum forces were acting (frames 24–25) and for the middle of the compartment (frame 29).

6. Discussion of results obtained in the study of fatigue strength of the joint between the frame and the double bottom structures in the fore hold of the ship

It can be seen from the results of the calculation of the magnitude of the range of operational loads acting on the compartment that their maximum falls on the forward half of the compartment. According to [14], this fact and appearance of cracks in the fore hold is explained by the maximum range of wave pressures and maximum vertical and transverse accelerations occurring at the ship extremities.

For the third version of side structure modernization, the magnitude of the range of internal forces decreased by about 2 times in comparison with the original side structure (Fig. 6 and Table 2). The decrease in internal forces is explained by a decrease in the design span of the frames due to the installation of a reinforced side girder in the middle of the hold height. Also, the stresses are reduced due to the extension of intermediate frames to the tank top. Such frames in the original version are ending above the double bottom at a level of the longitudinal tie of the side. Therefore, when calculating the range of moments from bending of the grillage and the beam, they should be included in the attached flange of the main frames.

Values of the scale parameter of distribution of the nominal equivalent stress ranges which depend on internal forces and change accordingly from one version of the side structure to another (Tables 3, 4).

It can be seen from an analysis of the results of fatigue calculation of a structural joint presented in Table 5 that the «full load condition» makes the greatest contribution to total fatigue damage of the joint.

Approximate taking into account of the slamming effect almost doubles the magnitude of the fatigue damage index in the «ballast condition». However, the magnitude of the measure of fatigue damage accumulated in this design condition was small relative to the cyclic damage accumulated in the «full load condition».

The results of calculating the fatigue damage of the joint with dimensions of the ties reduced by the value of corrosion allowance over 25 years are conservative since they were obtained on the assumption that thickness of the hull structures is reduced from the very beginning of the ship's operation.

It was shown in [9] that the calculated value of fatigue damage obtained by reducing the tie size by 25 % to take into account the effect of corrosive wear, corresponds to cyclic damage of the joint under conditions of «hard» corrosion. Moreover, the latter was determined on the basis of the measurement results. Comparative calculations were performed using the example of longitudinal stiffeners of the upper deck in a tanker (L_{pp}=235 m).

It was proposed in the normative document [16] to calculate the fatigue life of the ship hull structures as one combined with the fatigue life under operating conditions «in the air» and in a corrosive environment. Thus, it was taken into account that the structure is protected from corrosion for part of its service life. To calculate fatigue damage D of a structure under corrosion conditions, the D value obtained under «in the air» conditions must be multiplied by 2.

In the case when the value of total fatigue damage of structural joints D_{tot} calculated on the basis of tie dimensions without deducting the corrosion allowance significantly exceeded the critical value ($D_{tot}>1$), the effect of corrosion might not be taken into account.

If value of D_{tot} calculated on the basis of tie dimensions without deducting the corrosion allowance was less than or equal to the critical level ($D_{tot}\leq 1$), then the desired result was assumed to be between this value and D obtained with the corrosion allowance taken into account. The latter can be taken as true, with a margin in a safe direction.

The results of calculating the measure of fatigue damage of the ship hull structural joint by improved experimental and theoretical method with a coefficient of decrease in the endurance limit under irregular loading conditions of 0.675 were close to the results of calculation according to the DNV-GL and IIW normative documents (Tables 6, 7).

The third version of modernizing the structure of the compartment side involving installation of a reinforced side girder approximately in the middle of the hold height can be used on the ships built according to the basic drawings of the 1288 project. In the vessel in question, a platform was installed in the middle of the height of the compartment not attached to the sides and rested on a number of pillars. Therefore, in this case, it is advisable to attach the above structure to the sides.

The values of fatigue damage and durability presented in this study were obtained by calculation methods, therefore, they are approximate. To determine internal forces acting on the structural joints, a simplified approach was applied according to which the loads are determined in accordance with the norms of the Register of Shipping. To refine the calculations, other approaches to determining external loads can be applied. The latter can be determined on the basis of measurement results or using hydrodynamic methods and specialized software systems as was done in [4, 6–8].

In addition, calculations of the fatigue damage index are based on the use of a linear hypothesis and the results of fatigue tests of typical structural joints loaded with a constant amplitude. Fatigue tests under stochastic loading simulating actual loading can be considered the most correct way to determine the fatigue life of structural joints. This load should simulate the actual one. However, such tests are time-consuming, expensive, and require specialized equipment. This explains the wide application of calculation methods in practice.

It should also be noted that all calculations for versions 1 and 2 of the side grillage structure were performed using basic drawings of the 1288 project in which steel rolled section (asymmetrical flat bulb section No. 24^a) is used for main frames. Calculations for the third version were carried out assuming a modernized structure of the ship hull of the project in which symmetrical flat-bulb section HP220×10 was used for main frames. Taking into consideration the fact that the latter section was used in building the ship for which this study was carried out, the results of the calculation of fatigue damage for versions 1 and 2 of the side structure can be considered somewhat overestimated.

The results obtained in the study can be applied to other types of vessels with a transverse side framing system.

In the future, it is advisable to study how the level of fatigue strength of the joint considered in the present study changes along the ship length. Such studies can be useful in practice to identify critical areas along the length of the ships for which special attention should be paid to the fatigue life of their structures.

7. Conclusions

1. Values of the ranges of operational loads for the ship compartment were determined using regulations of classification societies. Values of bending moments resulting from grillage and beam bending at the points of fatigue cracks initiation along the compartment under consideration were determined with the application of the finite element method for original and modernized structure versions.

2. Parameters of long-term distribution (by Weibull's law) of ranges of nominal operating equivalent stresses in «hot spots» were calculated for the sections where maximum internal forces acted and for the middle of the compartment. These data have been determined with and without corrosive wear. Values of the scale parameter of the long-term distribution calculated 19.80; 16.85; and 13.73 MPa respectively for the original and two modernized versions of the ship side structure in the area of maximum internal forces. With a decrease in the tie cross-section by the value of corrosion allowance, the parameter values were 23.50; 19.86; and 16.26 MPa.

3. Values of the total fatigue damage and durability of the joints of the intersection of the main frames with the double bottom in the fore hold of the vessel were determined by the nominal stress and the hot spot stress approaches and the experimental and theoretical method. Calculations were made with and without corrosive wear. It was shown that in order to ensure a sufficient level of fatigue strength of the considered structural joints, it is necessary to extend the intermediate frames of the original version of the side structure to the level of the double bottom fixing them with knees to the tank top. Brackets must be attached in the plane of intermediate frames inside the double bottom. It is also necessary to attach a cargo platform to the side. As a result, the level of fatigue damage of joints over 25 years of operation will decrease by about 3.5 times

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