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REVEALING THE INFLUENCE OF STRUCTURAL JOINTS LOCATION IN A DRY CARGO SHIP ON DURABILITY PARAMETERS

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This work investigates the process of fatigue crack initiation in the structural joints of a dry cargo ship. The study addresses problematic issues related to changing the durability of the joints in the intersection of the longitudinal stiffener of the bottom and the floor, as well as the intersection of side structures and the double bottom along the length of the dry cargo ship.

Underlying the study is a simplified approach to determining external loads, the finite element method, the linear fatigue damage summation hypothesis, as well as the nominal stress approach.

Scientific ideas have been deepened about the regularities of changes in the parameters of the long-term load distribution on structural joints along the length of the dry cargo ship. The distribution scale parameter was taken as the criterion in the calculations. For the joint in the intersection of the longitudinal stiffener of the bottom and the floor, the distribution scale parameter increased when moving from the middle compartments of the ship to the bow by 5% for the loading condition "fully loaded vessel" and was unchanged for the loading condition "ship in ballast". For the junction of the bottom and frame structures, this parameter increased by 11–12% for the loading condition "fully loaded vessel" and by 11.8–13.7% for the loading condition "vessel in ballast".

It was established that the durability of both joints decreases from the middle part of the hull to the bow as follows: the junction of the longitudinal stiffener of the bottom and the floor – by 21%; the junction of the frame with a double bottom – by 42%.

The results are explained by the determining influence of local loads in the bow of the vessel. They could be applied in the field of shipbuilding and ship repair when designing dry cargo vessel structures and when planning hull condition inspections

Keywords: ship hull, finite element method, load, stress range, fatigue damage

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1. Introduction

Ship hull structures operate under difficult conditions that lead to the formation of fatigue cracks in critical areas of the ship hull with increased stresses. As noted in [1], cracks in ship hull structures account for half of the possible defects of such structures, and most of these defects are caused by metal fatigue. In some cases, according to the authors of [1], these cracks can reach significant sizes and lead to a decrease in the load-bearing capacity of individual structures and the hull as a whole, as well as to a loss of the latter's watertightness.

The basic types of variable loads according to [2] are:

– hydrodynamic, caused by the operation of the ship's propulsion system (high-frequency loads with a typical number of cycles of 10^{10} during the ship's service life);

– caused by changes in loading conditions, loading and unloading operations of the ship (low-frequency loading with very large periods, typically from 100 to 1000 cycles during the ship's service life);

– wave (low-frequency load with a frequency of the order of 0.1 Hz, subject to condition that the vessel has a service life of 25 years, the typical number of cycles can vary during this period from 10^7 to 10^8).

The main cause of fatigue cracks in the structural components of ship hulls is wave loads. A simplified method using regulatory documents of classification societies, a direct method, or a method based on the analysis of loads in the frequency domain can be used to determine them.

In practice, the nominal stress approach, the hot spot stress approach, and the notch stress approach are used for fatigue assessment of ship structures. These approaches are briefly described in [2]. The determining factors for the fatigue strength of ship structural joints are the level of stress concentration and the range of stresses acting on the joint. Recommendations for determining the values of stress concentration factors in the "hot spot" can be found in [3–6]. Recommendations for determining "effective" stress in the notch using the fictitious notch rounding approach are reported in [3–5, 7].

To determine the magnitudes of the ranges of stresses acting on ship structural joints, it is necessary to construct beam and shell models of individual hull elements, floors, and compartments, and, possibly, the hull as a whole. The construction of such finite element models is quite laborious.

It is obvious that the reliability of the calculation model in determining the magnitude of the stress range acting on the structural unit will have a direct impact on the validity of the results of calculating the fatigue strength and durability indicators. The interaction between the structural elements of the ship's hull is best reflected by three-dimensional detailed models, which can be beam or shell. At the same time, models with a high level of detail are laborious.

The simpler to implement are beam two-dimensional models, which are considered in classical courses of ship structural mechanics. In such models, ship structural grillages are considered isolated from the ship's hull with fixed or hinged supports at the boundary points where the grillage is combined with the adjacent one. Therefore, the interaction of the grillage with adjacent ones is not taken into account in such models.

Thus, it is of interest to compare the fatigue strength and durability indicators of typical structural joints obtained on the basis of two-dimensional and three-dimensional frame finite element models. The latter reflect the spatial interaction between the structural grillages that make up the compartment.

The same type of ship structural joints can be located in different parts of the ship's hull along its length. Moreover, the intensity of the cyclic load on the joint depends on its location in relation to the ship's extremities. Such a load is caused by the overall bending of the ship's hull on waves, local inertial forces, and sea water pressure. The relative contribution of each of the specified types of loads to the cumulative fatigue damage of the structural joint depends on its location in the ship's hull. For some structures, the load from the overall bending of the hull prevails, for others – local load. At the extremities of the ship, the magnitudes of the variable pressure on the hull from the action of sea water and waves, inertial and impact loads are significant [8]. However, the magnitudes of the amplitude of wave bending moments from the bending of the ship's hull in the vertical and horizontal planes reach maximum values in the middle part of the hull and decrease to zero when approaching the extremities.

In [9], using the example of an Aframax tanker, the importance of the criterion for ensuring fatigue strength in the design of ship hull structures was demonstrated computationally.

When designing ships and planning hull condition inspections, it is necessary to understand the position of probable fatigue failure sites. Therefore, studying the change in fatigue durability indicators of structural components along ship hulls is relevant.

According to the data reported in [10], in the world fleet, dry cargo ships account for the largest share of units over 20 years old. Therefore, ensuring the durability of the structures of such ships is relevant for their design, operation, and renovation.

2. Literature review and problem statement

In [8], the fatigue strength characteristics of the structures of a gas carrier with a length between perpendiculars $L_{BP} = 275$ m were studied. It was shown that the largest number of fatigue cracks in the cross-section of such a vessel occurred in the intersection points of the longitudinal stiffeners of the side with transverse structural members in the area below the load waterline. Structural joints of the bilge tanks also had low durability characteristics. The results reported in [8] allow us to get an idea of the areas with low durability in the characteristic cross-sections of the gas carrier under consideration. However, the cited work did not study how the durability of such joints changes in different sections along the length of the vessels. The information found can be used only for gas carriers and vessels with a similar hull design.

For trawlers, the fatigue of structural joints was studied in [11], in which frame models were used to determine the internal forces in the structures. The cited work investigated the joints of the frames and the double bottom in the bow cargo compartment of a trawler where fatigue cracks appeared as a result of the operation of the vessel. The authors studied the causes of their initiation, which are associated with the imperfection of the side structure and increased local loads in the bow compartment. Based on the results of the analysis, design recommendations and structural changes were proposed, but they cannot be applied to dry cargo vessels.

Papers [12, 13] report the results of fatigue studies on structural joints of a gas carrier and a tanker, obtained using a simplified approach to the assessment of operational loads on ship hull structures. In work [12], the results of the study of the durability of the intersection of longitudinal stiffeners and transverse structural members in the midship region of the gas carrier hull for the entire cross-section of the vessel are presented. The cross-section in the area of the intersection of these stiffeners with the transverse bulkhead was also studied. The work shows that the critical areas of such a vessel are the areas of the side below the waterline and the bottom. The results described also give an idea of the dangerous areas in the characteristic cross-sections of the vessel under consideration. However, the authors do not analyze the change in the durability of typical units along the length of the vessel.

In paper [13], the durability of structural joints of a tanker with a length between perpendiculars $L_{pp} = 225$ m was investigated. During the operation of this vessel, fatigue cracks were found in the area of the intersection of the longitudinal stiffeners and transverse structural members, at the junction of the brackets with the bulb. Most of the cracks were found in the side structures in cargo and ballast tanks. The paper reports results of a study on the durability of structural joints of the intersection of longitudinal stiffeners with a transverse structural members for the entire cross-section of the vessel in the midship region. The results of the study on the durability of joints of the intersection of longitudinal stiffeners with a transverse bulkhead, which were performed for the entire cross-section of the vessel, are also described. It was established that the joints in the area of the design waterline and a few meters from it to the bottom have the lowest durability. The largest contribution to the total fatigue damage of these joints is made by the variable pressure of sea water. The author's generalization of the results of research broadens the understanding of the durability indicators of structural components in typical ship sections. However, the information provided does not have practical value for determining the location of dangerous areas with insufficient fatigue durability along the length of the ship.

In [14], the results of studies on the fatigue strength of the coaming element of a container ship with a length of

$L_{pp} = 242$ m and a capacity of 3800 TEU are given. Fatigue calculations were performed in accordance with the Rules and recommendations by eight leading classification societies. It is shown that the results of fatigue strength assessment of the same structural unit may differ significantly when applying the Rules and recommendations by different classification societies. However, the authors' research is limited to calculations of the durability of the coaming element only in the cross-section of the vessel in the midship region. The durability of such a structural element is determined by the values of bending moments from the overall longitudinal bending of the hull in the vertical and horizontal planes, which vary along the length of the vessel, and this requires further elaboration.

Studies similar to [11–13] were performed in [15]. Using a simplified approach, the fatigue strength of the structural joints of the bulk carrier with a length between perpendiculars $L_{pp} = 179.37$ m was calculated. The joints of the intersection of longitudinal stiffeners and bottom transverses, structural joints of wing and bilge tanks were considered. The fatigue strength and durability characteristics of these joints were determined in accordance with the regulatory documents of classification societies, such as Bureau Veritas, Germanischer Lloyd, and Lloyd's Register. The results of the fatigue strength assessment also differed somewhat, although less significantly than in work [14]. The work found that the reason for the discrepancies between the presented results is the difference in the definition of operational loads in accordance with the regulatory documents of different classification societies and in the methods of fatigue assessment. It is worth noting that the distribution of operational loads on structures along the height and length of the vessel, determined according to the regulatory documents of different classification societies, can also differ significantly. Accordingly, the nature of change in the fatigue durability characteristics of such structures along the length and height of the vessels, determined on the basis of such loads, will differ. These issues were not considered in paper [15].

In [16], the results of the assessment of the accumulated cumulative fatigue damage over a 20-minute period of the structures of container ships with a capacity of 2800 TEU and 4400 TEU are reported. The values of fatigue damage of the structural elements of the upper deck were determined on the basis of the recording of the external load obtained during the operation of the vessels. The results of the assessment of fatigue damage were compared with the same values obtained when using several variants of the direct method for determining external loads. The authors determined that the results based on the application of the nonlinear panel method of external load assessment in combination with the finite element method are in the best agreement with the data obtained on the basis of measurements. However, the work did not consider the change in the fatigue durability characteristics of the structural elements of the upper deck in different sections along the length of the vessels.

In [17], a simplified approach similar to [15] to the assessment of the fatigue strength of structural joints of the intersection of side longitudinal stiffeners of of a supertanker with transverse web frames is described in detail. In [17], the results of the assessment of the vertical distribution of the magnitudes of the operational equivalent stresses along the height of the side with and without taking into account nonlinear effects are also given. Such stresses actually determine the level of fatigue durability of structural joints, so their distribution allows us to judge the position of critical points along the height of the side structure.

Most scientific papers study the durability of structures with an insufficient level of fatigue strength or the identification of dangerous areas in typical cross-sections of ships, which are characterized by low durability characteristics. Despite significant progress in research on the problem of fatigue strength of ship hull structures in recent decades, the influence of the location of typical structural joints along the length of the ship on their durability remains insufficiently studied.

3. The aim and objectives of the study

The purpose of our study is to identify the influence of the location of structural joints along the length of a dry cargo ship on their fatigue durability characteristics.

To achieve the goal, the following tasks were set:

– to establish patterns of changes in the parameters of long-term load distribution on structural joints along the length of the ship;

– using a calculated estimate, to analyze the change in the fatigue durability characteristics of structural joints along the length of the ship.

4. The study materials and methods

The object of our study is the process of fatigue crack initiation in the structural joints of a dry cargo ship.

The study is based on the hypothesis about the influence of the longitudinal arrangement of structural joints on a dry cargo ship on their loading parameters and fatigue durability characteristics.

To assess the fatigue strength of the structural joints of ship's hull, the following assumptions are adopted:

– the long-term distribution of the magnitudes of internal forces and, accordingly, stresses in ship hull structures is described by the two-parameter Weibull law; the parameters of such a long-term distribution can be determined using a simplified approach applying the regulatory documents in force in Ukraine;

– the values of magnitudes of operational equivalent nominal stresses acting on the structural joints can be represented as a combination of stresses from the general longitudinal bending of the ship's hull in the vertical plane, bending of the floor and beam;

– assessment of the fatigue strength of structures can be performed using the nominal stress approach; the criterion for fatigue failure is the development of a crack to its through-propagation through the cross-section of the structural element;

– fatigue of ship hull structures under stochastic irregular loading can be described using the linear hypothesis of fatigue damage summation.

The following simplifications were accepted in the study:

– fatigue calculations were performed at the design thicknesses of the joints; wear of the cross-sections of the joints was not taken into account, since the purpose of the work was not to predict the durability of structures;

– the effect of corrosion on the fatigue strength of structural joints was not taken into account for the same reason;

– it was assumed that the ship is straight-walled with constant dimensions within compartments 2–5;

– it was assumed that the cargo pressure acts only on the bottom structures in the loading condition “fully loaded vessel”;

– the distributed load on the structures was calculated for the average cross-section of each compartment and grillage; it was assumed that it is constant along their length.

The cross-section of the ship, the structures of which were studied for fatigue, is shown in Fig. 1. The design data on this ship are given in Table 1. Some load characteristics in the loading conditions “fully loaded vessel” and “ship in ballast” are given in Table 2. As initial data (Tables 1, *2)* for calculations, archival materials, and results of educational developments from the Department of Structural Mechanics and Ship Hull Design, the Admiral Makarov National University of Shipbuilding, were used. The values of the moment of inertia of the midship section relative to the horizontal axis I_m, the draft by the bow and stern T_f, T_a, the still water vertical bending moment in the midship section M_{sw} were obtained by calculation.

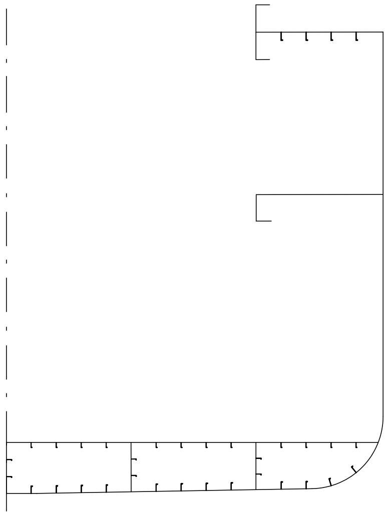


Fig. 1. Midship section diagram of a general cargo vessel

Table 1

Estimated data on the studied vessel

Length between perpendiculars L_{pp}, m	139
Width B, m	19.4
Depth D, m	12.2
Block coefficient-C_b	0.66
Speed v, knot	15.5
Moment of inertia of the midship section relative to the horizontal axis I_m, m^4	33

Table 2

Characteristics of loading conditions of the vessel

Estimated state	Fully loaded vessel	Ship in ballast
Forward draft T_f, m	8.65	6.71
Draft aft T_a, m	8.37	4.49
Displacement Δ, t	15400	8694
Vertical still water bending moment amidships M_{sw}, t·m	27050	52550

The studies were performed for typical structural joints of a dry cargo ship. In the first case, the intersection joint of the longitudinal bottom stiffener and the floor (Fig. 2) was considered, which is typical for ships with a longitudinal framing system of a bottom. This joint simultaneously experiences the load from the action of local pressure of sea water and cargo on the bottom structure and bottom stiffener, as well as from the overall longitudinal bending of the ship’s hull in waves.

In the second case, the structural joint of the frame and double bottom structures intersection (Fig. 3) was investigated with a transverse side framing system. It was assumed that this joint experiences only local loads from the bending of the side grillage structure and the frame in the hold due to the action of seawater pressure. It also experiences reactive loads from the interaction of the side grillage with the bottom and deck grillages. For both typical joints, calculations were performed for ship cross-sections close to the middle of compartments 2–5.

In general, a structural joint may include several concentration sites, and the durability of these sites is different. Considering that the purpose of our study is to analyze the change in the durability of typical structural joints along a dry cargo ship, and not to predict the fatigue life of these joints , the concentration sites were selected approximately. Finite element analysis of structural joints was not performed. The concentration sites marked in Fig. 2, 3 were selected as the studied concentration sites.

The calculation of the magnitudes of the acting forces in ship hull structures was performed using the finite element method, the main provisions of which are set out in [18]. Finite element analysis was performed using the open software complex Salome-Meca.

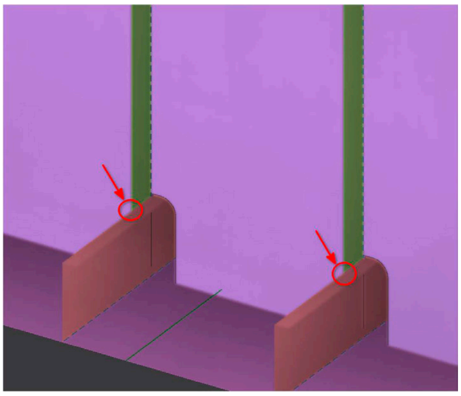


Fig. 2. The site of stress concentration at the intersection of the longitudinal stiffener of the bottom and the floor of a dry cargo ship

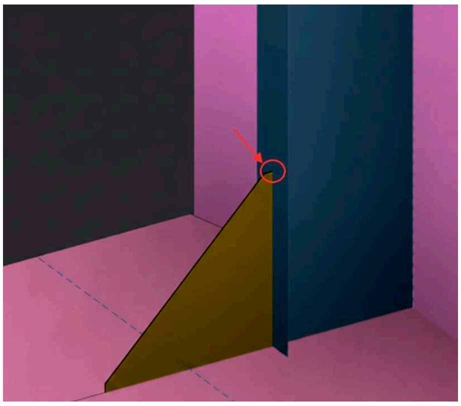


Fig. 3. Site of stress concentration at the intersection of the bottom and frame structures of a dry cargo ship

The features of finite element modeling were as follows:

– the studies were performed on the basis of two-dimensional and three-dimensional frame models;

– the cross-section of the frame beam model included three adjacent frames, as shown in Fig. 4;

– brackets and knees were not modeled for simplicity.

The following boundary conditions were applied:

– fixed supports were assumed at the ends of longitudinal strength members, such as vertical keel, stringers, carlings, and coaming-carlings;

– joints of frames with double bottom structures were hinged.

Similarly to work [11] and in accordance with the recommendations from [5] and [19], the fatigue strength of ship hull structures was assessed using the linear hypothesis of fatigue damage summation. Fatigue damage D with continuous long-term load distribution on the ship hull structural joint in the i-th loading conditions of the ship can be determined from the following formula

$$D_i = \alpha_i N^* \int_{(\Delta\sigma_n)_{\min}}^{(\Delta\sigma_n)_{\max}} \frac{p_i\left(\Delta\sigma_n\right)}{N\left(\Delta\sigma_n\right)} \mathrm{d}\left(\Delta\sigma_n\right), \tag{1}$$

where $\Delta\sigma_n$ is the nominal stresses range; $p_i(\Delta\sigma_n)$ is the probability density of the distribution of the $\Delta\sigma_n$ value in the i-th loading condition of the vessel; $N(\Delta\sigma_n)$ is the dependence of the number of cycles to fatigue failure (or the appearance of a fatigue crack of a certain length) on the value $\Delta\sigma_n$; $N(\Delta\sigma_n)$ is the dependence of the number of cycles to fatigue failure (the appearance of a fatigue crack of a certain size) on the value $\Delta\sigma_n$; $(\Delta\sigma_n)_{min}$, $(\Delta\sigma_n)_{\max}$ are the minimum and maximum ranges of nominal stresses in the load range of the studied object for the loading condition under consideration; N^* is the number of load cycles during the design life of the vessel; α_i is the fraction of the vessel being in the i-th loading condition.

The probability density of the stress distribution according to the Weibull law is expressed by the following dependence

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

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

The k_w, a_σ parameters, according to [5, 9], can be determined from the following formulae:

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

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

where L is the length of the vessel, m; $(\Delta\sigma_n)_{ch}$ is the magnitude of the range of characteristic nominal operational stresses with a probability of their occurrence of $1/N_{ch}$, Pa.

It was assumed that the $(\Delta\sigma_n)_{ch}$ value is equal to the value of the equivalent operational nominal stresses $\Delta\sigma^{\Sigma}$, which are determined from the following formula

$$\Delta\sigma^{\Sigma} = \sqrt{\sum_{j=1}^{3}\Delta\sigma_j^2 + 2\sum_{j=3}^{3}\sum_{v=1}^{3}\rho_{jv}\Delta\sigma_j\Delta\sigma_v}, \tag{5}$$

where $\Delta\sigma_j$ are the components of the ranges of variable stresses from the overall longitudinal bending of the ship's hull ($j = 1$), from the bending of the grillage ($j = 2$) and the bending of the beam under consideration ($j = 3$); $\rho_{jv} \approx \pm 0.5$ is the correlation coefficient of the component stresses (the sign "+" or "–" depends on the location of the "hot" point in the structure).

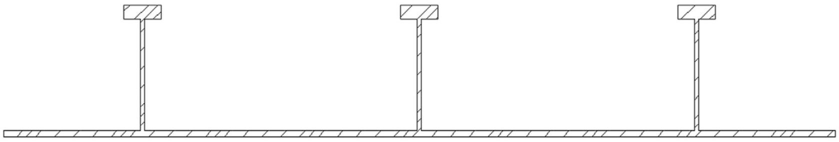


Fig. 4. Cross section of the frame beam model

When calculating the $\Delta\sigma^{\Sigma}$ values, the correlation coefficients ρ_{jv} were taken in such a combination that $\Delta\sigma^{\Sigma}$ had the largest possible values, and the calculated values of fatigue damage D_i were with a margin in the safe side. This approach is justified, given that the purpose of the study is to analyze the change in the durability of typical joints along the ship.

Taking into account the location of the "hot" points (Fig. 2, 3) and the use of frame finite element models, the $\Delta\sigma_j$ components in (5) were determined from the following formula

$$\Delta\sigma_{1,2,3} = \frac{\Delta M_{1,2,3}\cdot z_{1,2,3}}{I_{1,2,3}}, \tag{6}$$

where ΔM_1, ΔM_2, ΔM_3 are the magnitudes of the bending moments in the "hot spot", respectively, from the overall bending of the ship's hull, the bending of the grillage structure and the bending of the beam; z_1, z_2, z_3 are the distances of the point under consideration from the neutral axes, respectively, of the equivalent hull girder, vertical keel or stringer or frame together with the attached plating, as well as the beam including the hot spot; I_1, I_2, I_3 are the moments of inertia of the cross sections of the equivalent hull girder, vertical keel or stringer or frame together with the attached plating, and the beam, respectively.

The $1 / N_{ch}$ value was assumed at the level of 10^{-5}, in accordance with the strength standards for seagoing vessels in force in Ukraine. The $\Delta\sigma^{\Sigma}$ values were determined for both structural joints under consideration, located in the middle of compartments 2–5, for the loading conditions "fully loaded vessel" and "ship in ballast". It was assumed in accordance with [5] that the ship was in the first loading condition for 75% of the service life, and 25% in the second.

The total fatigue damage of the structural joint over the design life of the ship D_{tot} without taking into account the influence of corrosion and its durability T_f can be determined using the following dependences [5]:

$$D_{tot} = D_1 + D_2, \tag{7}$$

$$T_f = T_d / D_{tot}, \tag{8}$$

where D_1, D_2 are the values of fatigue damage to the structural joint accumulated in the loading condition "fully loaded vessel" and "vessel in ballast", respectively; T_d is the planned service life of the vessel, years.

It was assumed that fatigue failure of the joint occurs at $D_{tot} = 1$. The influence of average cycle stresses was not taken into account when estimating the D_{tot} value.

A three-dimensional frame model of a compartment with an applied operational load from wave action with a probability of exceedance of 10^{-5} is shown in Fig. 5. Such a model was used for compartments 2–5.

Fig. 6 shows a two-dimensional model of the bottom grillage under an applied operational load. Such a model was used to model the bending of the bottom grillages in compartments 2–5. It should also be noted that according to regulatory documents, the design pressure on the vessel structures was limited to some estimated minimum values.

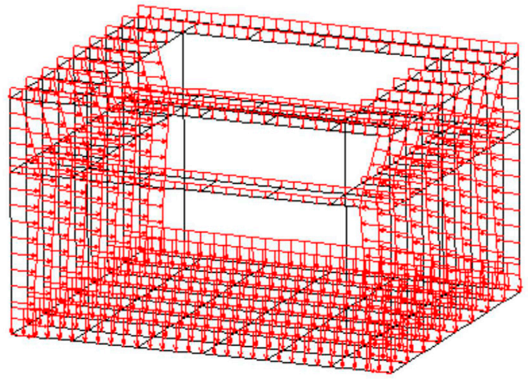


Fig. 5. Frame 3D model of a compartment under an applied load

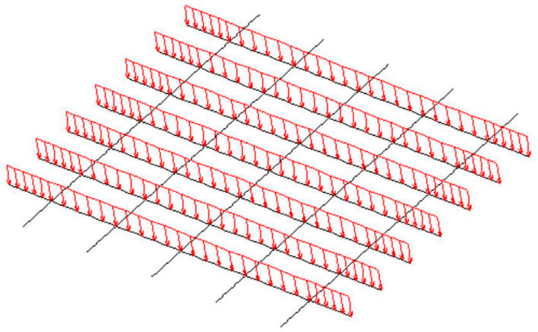


Fig. 6. Frame two-dimensional model of the bottom grillage under applied load

The calculation scheme of the side structure, selected in accordance with [20], is shown in Fig. 7. This scheme was used to determine $\Delta\sigma_2$ from the bending of the side grillage for the junction of the bottom and frame structures. Fixed support was assumed at the level of the tank top, and hinged supports at the level of the intermediate and upper decks. The following symbols are used in the figure: p_w^{UD}, p_w^{WL}, p_w^{TT} – values of the calculated range of a distributed wave load at the level of the upper deck, waterline, and tank top.

The calculation scheme of the frame in the hold for determining $\Delta\sigma_3$ for the structural junction of the bottom and frame structures is shown in Fig. 8. The same symbols are used in this figure as in Fig. 7.

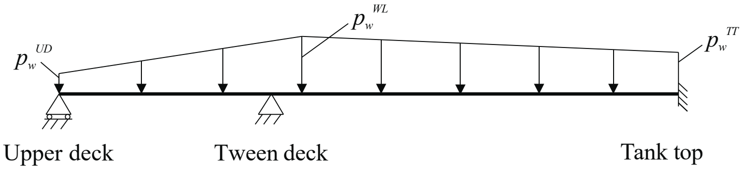


Fig. 7. Calculation scheme of the side structure [20]

The calculation scheme for determining $\Delta\sigma_3$ from the bending of the beam at the intersection of the longitudinal stiffener of the bottom and the floor is shown in Fig. 9, where p_w^{DB} is the value of the calculated range of the load on the double bottom.

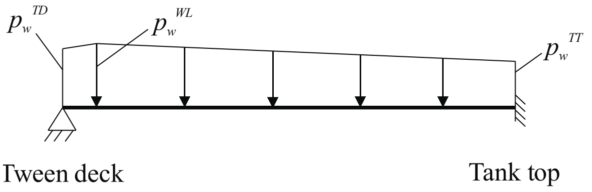


Fig. 8. Calculation scheme of the hold frame [20]

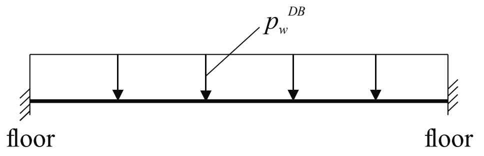


Fig. 9. Calculation scheme of the bottom stiffener [20]

As mentioned above, the nominal stress approach was chosen for fatigue calculations. This method involves the typification of critical areas of a structural joint according to the classification given in [3, 4]. Based on the results of typification of critical areas, they are assigned a FAT (fatigue class) digital code. This fatigue class corresponds to the endurance limit of the structure at $2 \cdot 10^6$ load cycles. For the one shown in Fig. 2 of the site of stress concentration at the junction of the longitudinal stiffener of the bottom and the floor, fatigue class 45 is chosen. And for the one shown in Fig. 3, fatigue class 63 was chosen for the concentration site at the junction of the bottom and frame structures.

5. Results of the calculation study on a change in the durability of typical structural joints along the length of the ship

5. 1. Results of determining the parameters of the long-term load distribution on structural joints along the length of the ship

As a result of calculations using the finite element method, the values of the bending moment ranges in the “hot spot” ΔM_1, ΔM_2, ΔM_3 from the overall bending of the ship’s hull, the bending of the grillage, and the bending of the beam were established. The corresponding values of the nominal stress ranges $\Delta\sigma_1$, $\Delta\sigma_2$, $\Delta\sigma_3$ were determined from formula (6). The calculations were performed for the joints shown in Fig. 2, 3 for two loading conditions: “fully loaded vessel” and “ship in ballast”. The joints located in cross sections in the middle of compartments 2–5 were studied.

An example of a bending moment range diagram obtained using finite element analysis for compartment number 2 in the loading condition “fully loaded vessel” is shown in Fig. 10.

Based on the calculated $\Delta\sigma_1$, $\Delta\sigma_2$, $\Delta\sigma_3$ values, the values of equivalent operational nominal stresses $\Delta\sigma^{\Sigma}$ were determined from formula (5). The shape parameter k_w of the long-term distribution of nominal stresses according to the Weibull law (2), determined on the basis of (3), was 1.055. The parameters of the scale of the distribution of nominal stresses a_σ, calculated from formula (4), for structural joints in the middle of compartments 2–5, the loading conditions “fully loaded vessel” and “vessel in ballast”, are given in Table 3. The a_σ value, as follows from (1), (2), has a direct impact on the value of the total fatigue damage D_{tot}, it can be considered as a characteristic of the long-term distribution of the external load on the ship's hull structures. Table 3 gives results of the a_σ calculation obtained when using two-dimensional and three-dimensional finite element frame models to determine the component $\Delta\sigma_2$ from the bending of grillages.

Hence, it follows from the data in Table 3.

Table 3

Parameter of scale of the distribution of nominal stresses in ship hull nodes

Structure ID	Distribution scale parameter a_σ, MPa			
	Compartment 2	Compartment 3	Compartment 4	Compartment 5
Results obtained on the basis of two-dimensional frame models of ship grillages				
Loading condition «fully loaded vessel»				
Intersection point of the bottom longitudinal stiffener and the floor	8.75	8.66	8.20	8.31
Intersection of bottom and frame structures	29.66	26.44	26.44	26.44
Loading condition «vessel in ballast»				
Intersection point of the bottom longitudinal stiffener and the floor	6.89	7.22	6.90	6.83
Intersection of bottom and frame structures	31.43	28.07	28.15	28.12
Results obtained based on three-dimensional frame models of compartments				
Loading condition «fully loaded vessel»				
Intersection point of the bottom longitudinal stiffener and the floor	9.33	9.16	8.70	8.81
Intersection of bottom and frame structures	24.82	22.18	22.40	22.35
Loading condition «vessel in ballast»				
Intersection point of the bottom longitudinal stiffener and the floor	6.50	6.83	6.55	6.48
Intersection of bottom and frame structures	29.75	26.78	26.25	26.16

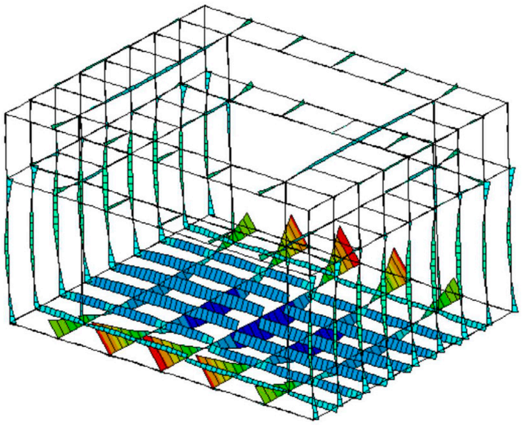


Fig. 10. Bending moment range diagram for compartment number 2 in the loading condition "fully loaded vessel"

For the structural joint of the intersection of the bottom longitudinal stiffener and the floor, the a_σ parameter increased insignificantly when moving from the middle compartments of the vessel 4–5 to the bow compartment 2: by 5% for the loading condition "fully loaded vessel" and was almost constant for the loading condition "vessel in ballast".

For the structural joint of the intersection of the bottom and frame structures, the a_σ parameter increased by 11–12% for the loading condition "fully loaded vessel" and by 11.8–13.7% for the loading condition "vessel in ballast".

The difference between the maximum values of the a_σ parameter determined using both models was as follows: 6% for the node of the intersection of the longitudinal stiffener of the bottom and the floor for both loading conditions of the vessel; 19.5% and 5.65% for the intersection of the bottom and frame structures, loading conditions "fully loaded vessel" and "vessel in ballast", respectively.

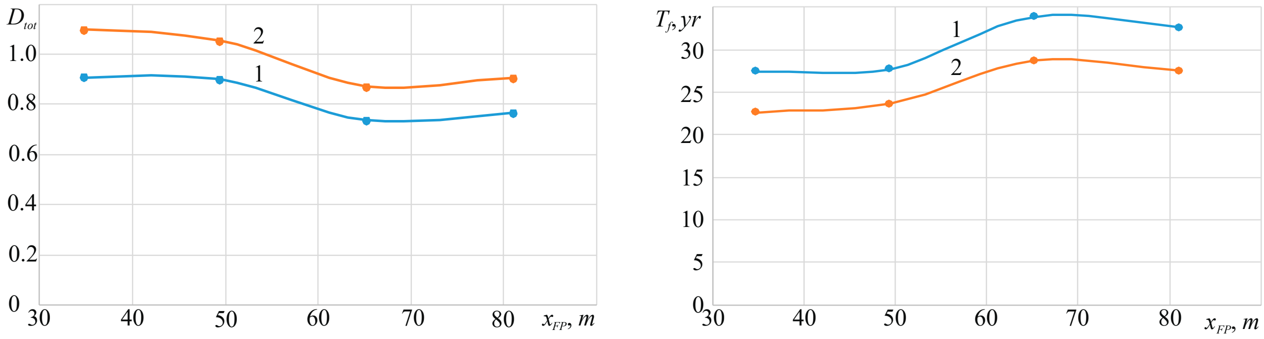
5. 2. Results of determining the change in fatigue characteristics of structural joints along the length of the ship

The calculated values of total fatigue damage of the studied structural joints for the estimated service life of the vessel D_{tot} without taking into account the effect of corrosion are shown in Fig. 11, 12, *a*, as a function of the distance of joints to the forward perpendicular x_{FP}. Fig. 11, 12, *b* show the results of determining the value of durability T_f of structural joints as a function of x_{FP}. The D_{tot} values were determined from formula (7), and T_f – from formula (8). The planned service life of the vessel T_d in the calculations was assumed equal to be 25 years according to [21].

From the curves shown in Fig. 11, it is seen that the results of using two-dimensional models of bottom structures to determine fatigue damage and durability of structural joints of the intersection of the longitudinal stiffener of the bottom and the floor were close to the results obtained using the three-dimensional model of compartments. The maximum difference in durability indicators was approximately 20%. This is due to the fact that in the case of this structural joint, the equivalent operational stresses according to formula (5) are a combination of three components $\Delta\sigma_1$, $\Delta\sigma_2$, $\Delta\sigma_3$, approximately the same in magnitude. Therefore, the difference in the $\Delta\sigma_2$ value due to the use of frame two-dimensional models or three-dimensional models does not significantly affect their combination $\Delta\sigma^{\Sigma}$ and the corresponding D_{tot} and T_f values. It also follows from these results that the D_{tot} value of fatigue damage of a typical joint from Fig. 2 increases when moving from the middle part of the vessel to the bow end by approximately 25%, and the fatigue durability T_f, accordingly, decreases by 21%.

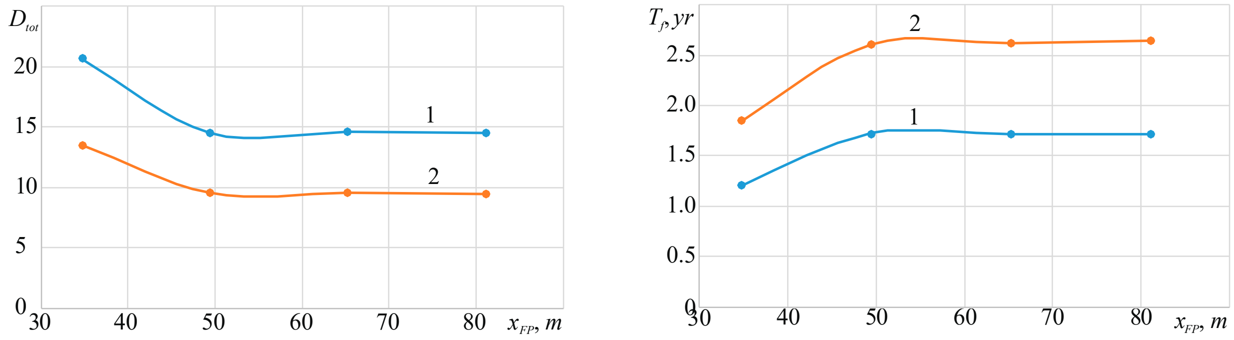
The difference between curves 1 and 2 in Fig. 12, *a*, obtained for the joint shown in Fig. 3, using two-dimensional and three-dimensional finite element models, is about 50%. The difference between curves 1 and 2 in Fig. 12, *b* is about 35%. As can be seen from these results, the use of two-dimensional frame models of the side grillage (Fig. 7) leads to significantly overestimated values of the $\Delta\sigma_2$ component in formula (5) and, accordingly, to overestimated values of fatigue damage D_{tot} in comparison with the results obtained using three-dimensional frame models of the compartment.

The structural joint in the intersection of the double bottom and frame is generally subjected to only local loads; therefore, the magnitude of the range of equivalent operational nominal stresses $\Delta\sigma^{\Sigma}$ acting on the joint is determined only by the $\Delta\sigma_2$, $\Delta\sigma_3$ values. The model, an example of which is shown in Fig. 5, allows us to better reflect the operation of the joint in the compartment as a whole as, in this case, the spatial interaction between the grillages in the compartment is taken into account.



a *b*

Fig. 11. Results of fatigue calculations of structural joints in the intersection of the longitudinal stiffener of the bottom and the floor: *a* – dependence of the value of the total fatigue damage D_{tot} on the distance to the forward perpendicular x_{FP}; *b* – dependence of the value of durability T_f on the distance to the forward perpendicular x_{FP}; 1 – curves calculated using two-dimensional beam models of ship grillages; 2 – curves calculated using three-dimensional beam models of ship compartments



a *b*

Fig. 12. Results of fatigue calculations of joints in the intersection of the bottom and frame structures: *a* – dependence of the total fatigue damage value D_{tot} on the distance to the forward perpendicular x_{FP}; *b* – dependence of durability value T_f on the distance to the forward perpendicular x_{FP}; 1 – curves calculated using two-dimensional beam models of ship grillages; 2 – curves calculated using three-dimensional beam models of ship compartments

From the results shown in Fig. 12, it follows that the value of the total fatigue damage D_{tot} of the structural joint in the intersection of the double bottom and frame increased when moving from the middle compartments of the vessel 4, 5 to the bow compartment 2 by approximately 42%. The drop in the T_f value of durability of the joints when moving from the middle compartments to the forward compartment was about 30%.

6. Discussion of results based on the study of change in the durability of typical structural joints along the length of the vessel

Fig. 10 shows that the largest values of the bending moment ranges ΔM_2 in the longitudinal strength members of the bottom act in its middle and at the extreme points along its length. The latter correspond to the intersection points of the longitudinal strength members of the bottom with the transverse bulkhead.

The largest ΔM_2 values of bending moment ranges in the intersection points of the frames with the bottom were the largest in the sections located in the middle of the compartment. In reality, the cross-section with the largest internal forces is somewhat shifted to the bow of the compartment, as shown in [11]. This is due to the fact that the amplitude of the wave pressure on the structure increases when moving from the aft to the bow of the compartment.

The results of determining scale parameter a_σ of the long-term load distribution on the structural joint of the intersection of the bottom longitudinal stiffener and the floor, given in Table 3, are explained as follows. This joint experiences variable loads from the overall bending of the hull and from the action of local loads. In the middle part of the vessel, according to the strength standards for seagoing vessels, the value of the calculated range of the vertical bending moment is the largest and decreases when approaching the extremities. The calculated wave loads, on the contrary, increase when approaching the bow. From the data in Table 3 it follows that the rate of increase in the values of the components $\Delta\sigma_2$, $\Delta\sigma_3$ from the local load when approaching the bow of the vessel exceeds the rate of decrease in the component $\Delta\sigma_1$ in formula (5). This causes a small increase in the a_σ and D_{tot} values for a typical joint of the intersection of the longitudinal stiffener of the bottom and the floor when approaching the bow extremities.

The structural joint of the frame and the double bottom is subjected to only local loads. The intensity of the latter increases as it approaches the forward end of the vessel, which corresponds to the data given in Table 3. This causes a decrease in the durability T_f of this typical joint as it approaches the forward perpendicular, as can be seen from the nature of both curves in Fig. 12.

The results shown in Fig. 11 are consistent with the results of the calculation of fatigue damage D_{tot} and durability T_f, given in [15] for a similar joint of a bulk carrier. In [15], however, another stress concentration site was chosen, which was also located at the junction of the floor stiffener and the bottom longitudinal. These results are also consistent with the results in [8, 12, 13], in which similar structural joints of other types of vessels were considered.

The values of total fatigue damage D_{tot} and durability T_f, shown in Fig. 12, are excessively conservative, which is associated with the conservativeness of the parameters of the long-term load distribution (Table 3). The results of the D_{tot} assessment for similar structural joints of the intersection of the bottom structures and the frame of a trawler, given in [11], were smaller. This difference can be justified by the fact that in [11] the calculations of operational loads were performed according to more modern regulatory documents on the strength of seagoing vessels.

In general, the nature of the curves in Fig. 12 is consistent with the experience of operating a trawler vessel described in [11]: fatigue cracks appeared in joints of the same type in the bow compartment of the vessel.

Our results of calculating the external load distribution parameter a_σ could be used for approximate estimates of the D_{tot} and T_f values for stress concentration sites in similar structural joints of similar vessels.

The results of change in the fatigue durability T_f of structural joints along the length of a dry cargo ship could be applied to vessels with a longitudinal framing system of the bottom, a transverse side framing system, and a similar hull length. Similar calculations of the fatigue durability of ship hull joints can be performed for a specific route of operation of the vessel using the methodology given in [22].

The previously noted conservatism in the results shown in Fig. 12 can also be explained by the simplifications that were used in the construction of three-dimensional frame finite element models of compartments, an example of which is shown in Fig. 5. To determine more accurate values of stress ranges in the side structural members, the compartment model should include bilge brackets, which could make it possible to model the frames on each frame spacing. In addition, the calculations were performed assuming the invariance of the cross-section of the ship's hull, which obviously leads to certain errors in determining the stress components $\Delta\sigma_1, \Delta\sigma_2, \Delta\sigma_3$. However, reducing the span of structural members will lead to a decrease in the stresses acting in them. Therefore, it can be assumed that the assumption about the invariance of hull cross-section along the length of the ship when performing stress calculations led to somewhat conservative results.

It is also worth noting that choosing the values and signs of correlation coefficients ρ_{jv} between the components of range of the equivalent operating stress in formula (5) is based on certain assumptions.

In further studies, plots could be constructed similar to those shown in Fig. 11, 12, for typical structural joints of dry cargo vessels of various lengths, as well as for vessels of other types. At the same time, difficulties may arise due to the lack of publicly available data on vessels of various types and lengths regarding their design and load distribution in the main loading conditions.

Also, in the future, the influence of wear and corrosion on the value of fatigue durability T of the considered structural joints could be approximately taken into account, according to the methodologies given in [3, 9]. It is obvious that such results will be smaller than those reported in our work.

7. Conclusions

1. The regularities of change in the parameters of the long-term load distribution on structural joints along the length of a dry cargo ship have been established, in which the scale parameter was taken as a criterion in the calculations. For the joint of the intersection of the longitudinal stiffener of the bottom and the floor, this parameter increased when moving from the middle compartments of the ship to the bow by 5% for the loading condition "fully loaded vessel" and was almost unchanged for the loading condition "vessel in ballast". For the structural joint of the intersection of the bottom and side structures, the scale parameter increased by 11–12% for the loading condition "fully loaded vessel" and by 11.8–13.7% for the loading condition "vessel in ballast". The results are explained by the predominance of the action of local loads in the forward region of the ship.

2. Using the nominal stress approach and the linear fatigue damage summation hypothesis, a calculation assessment and analysis of the change in the fatigue durability characteristics of structural joints along the length of the vessel was performed. It was established that the durability of both joints decreases from the middle part of the hull to the bow as follows: the joint of the intersection of the longitudinal stiffener of the bottom and the floor – by 21%; the joint of the intersection of the frame with a double bottom – by 42%. Such results are also explained by the predominance of the action of local loads in the bow part of the vessel.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Dmytro Lytvynenko: Conceptualization, Methodology, Validation, Formal analysis, Writing – original draft; Writing – review & editing; **Oleksandr Shchedrolosiev:** Conceptualization, Validation, Writing – original draft, Project administration; **Yuliia Kazymyrenko**: Validation, Writing – original draft; Writing – review & editing; **Hanna Konovalova:** Writing – original draft.

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