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Development of Constructive Measures to Reduce the Consequences of Ship Collisions

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Abstract

An analysis of the damage caused to vessels by collisions shows that the wreck of most struck ships is mainly due to underwater damage developed because of the accident. Such damage is caused, as a rule, by the presence of bulbs on striking ships that have high longitudinal rigidity and strength exceeding the load-bearing capacity of the framing system several times. Scientists in many countries are looking for ways to reduce the consequences of collisions with ships that have bulbs. Based on the results of the research, schemes for modernizing the forward end of ship hulls by installing bulbs with increased longitudinal compliance to reduce the consequences of ship collisions were proposed, and recommendations were developed for the selection of their characteristics, which make it possible to avoid underwater holes on a struck ship. Bulbs with increased longitudinal compliance were designed using methods of plastic limit analysis. The effectiveness of a modernized deformable bow structure was studied using ANSYS LS-DYNA non-linear finite element method computations. The developed technical solutions ensure that in case of collision in the underwater part of a struck vessel, the deformations of the framing systems will remain insignificant, thereby avoiding the appearance of damage below the waterline.

Keywords: Ship collisions, Corrugated bulb, Bearing capacity, FEM, Plastic limit analysis

1. Introduction

An analysis of the damage caused to vessels by collisions shows that the wreck of most struck ships is mainly due to underwater damage developed because of the accident [1,2]. Such damage is caused, as a rule, by the presence of bulbs on striking ships that have high longitudinal rigidity and strength exceeding the load-bearing capacity of the framing system several times.

According to some data [1], in 80% of cases, damage to struck ships is located below the operational waterline, and the probability of ship destruction is determined by the size of the damage and the design features of the ship (position of watertight bulkheads, distance between double sides, etc.) affecting the number of compartments flooded [1,3].

In [4], it is shown that for more than 30% of the collision scenarios, the damage vertical position lower limit is above the waterline, but typically due to scenarios with collision angles close to 0° or 180° with limited penetration. During the risk assessment, the scenarios leading to these damages were discarded, and damage stability analysis was carried out [4]. In the study [5], it is shown that the bulb structure is most threatening to struck ships. In paper [6], a bulbous bow is a threat to a struck ship because most large ships have a bulbous bow and it usually contacts the struck ship first, then it might penetrate the side shell.

A typical example of the influence of bulb design on the consequences of an accident is the collision of the SS "Admiral Nakhimov" with the MS "Pyotr Vasev" that occurred on August 31, 1986 in Tsemes Bay near Novorossiysk. It resulted in the loss of 423 lives [2,7]. The MS "Petr Vasev" crashed into the hull of the SS "Admiral Nakhimov" in the area of 90-110 frames on the starboard side with the upper part of the stem and the bulb below the waterline. The bulb ripped up an underwater hole in the ship's hull with an area of 84 m^2 stretching from the seventh to tenth watertight compartments that housed the second boiler room, engine room, tanks with fuel oil and diesel fuel, food warehouses, and hold No. 4. At the same time, the bulb of the striking ship remained practically undeformed [2,7].

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It is known that the use of bulbs can reduce wave resistance by approximately 15% or more, depending on the hull design. However, there is a contradiction between a small gain in speed, and a few percent in fuel economy, and colossal losses in the case of collision. If there is a bulb on the striking ship, the struck ship in case of collision, even at low speed, receives damage below the waterline that often leads to a ship wreck. The economic side of this issue is also a subject of ship insurance because insurers consider the issue of "taking into account bulbs in insurance conditions" [8,9].

2. Analysis of the Existing Design Solutions

Scientists in many countries are looking for ways to reduce the consequences of collisions with ships with bulbs [10-13]. The concept of soft bow design was proposed in [14]. Thus, in 1990, Woisin [8] developed recommendations for reducing the consequences of collisions with ships with bulbous bows. It was proposed to reduce the size of the bulb shapes or to make the bulb flexible in the longitudinal direction so that it would collapse under low longitudinal force, while the force destroying the bulb should be less than that which violates the integrity of the shell plate of the framing system.

As an alternative to a bulbous bow to reduce the consequences of collisions, according to Woisin [8], the Mayer's bow shape should be considered. It is also recommended to reduce the thickness of the shell plate and stem to create a "lightweight" structure, but the practical implementation of these provisions has not yet been carried out.

In paper [15], the probability of rupture of cargo oil tank in the struck VLCC in cases where all the spiking ships use buffer bulbous bows was compared with the case where all the striking ships use conventional bulbous bows. It is estimated from the calculation that the probability of rupture of cargo oil tank in the struck VLCC decrease about 10-12% by the effect of using buffer bulbous bow.

In [16], various softening methods for the fore part of an LNG carrier are proposed and their influence on reducing the damage of a struck ship and the impact transmitted to the striking ship are studied. The effectiveness of a buffer bow is highlighted in [5] by focusing on the performance and how much the risk of oil outflow is decreased. In [17], the introduction of buffer bulbous bows has been proposed. Relatively soft buffer bows absorb part of the kinetic energy of the striking ship before penetrating the inner hull of the struck vessel.

Papers [6] and [18] show that buffer bow design (bulbous bow stiffened with vertical ring frames) may effectively reduce the risk of oil spill and/or seawater ingress in various cases of collision between large ships. It is noted that a lower crushing pressure of the bulbous bow is preferable to avoid the early and easy rupture of the side structure.

A comparative collision study of the new SEA-Arrow buffer bow and the conventional bulbous bow was conducted in [19] using elasto-plastic finite element analysis. It is shown that the buffer bow characteristic of the SEA-Arrow is superior to that of the conventional bulbous bow because much more energy is dissipated by the plastic deformation of striking and struck ships until the inner shell of the struck ship ruptures.

To reduce the consequences of collisions with ships equipped with bulbs, new designs of bow bulbs have been proposed [13,20,21]. It is possible to eliminate underwater damage by making the longitudinal bearing capacity of the bulb lower than the bearing capacity of the side framing system of the vessels, which is achieved by making the shell plate of the bulb in the form of annular corrugations.

This design of the bulb has a cone-shaped or cylindrical shape, contains a fairing and an insert made in the form of corrugations and reinforced with brackets, and the cross-sectional corrugations of the insert have the shape of a drop or a circle. These designs have some disadvantages; therefore, this paper proposes new technical solutions.

Thus, in the bulb design [21], the ultimate load for corrugations with a large perimeter is significantly higher than that for corrugations with a small perimeter located in the bow part of the bulb, which leads to an increase in the longitudinal rigidity of the bulb. Reducing the longitudinal rigidity of the bulb is possible by increasing the height of the corrugations with an increase in their perimeter; however, this leads to a loss of useful volume inside the bulb and also increases the labor intensity of manufacturing the bulb because of the need to manufacture corrugations of various heights.

An increase in the compliance of the bulb due to a decrease in the thickness of the corrugations is limited by the fact that during operation, the bow end of the ship is subjected to intense hydrodynamic loads.

This paper presents new design solutions that make it possible to regulate the compliance of bulb fitting within a wide range through the implementation of some measures. In particular, to regulate the compliance of the corrugated insert, it is proposed to use grooves of a certain depth in the corrugations. To fill the space in the corrugations to give the bulb fitting a streamlined shape, it is proposed to use elastic containers with a working medium. In addition, the bulb fitting can be made of separate sections that slide inside the bulb during the interaction of the bulb fitting with the side grillage of the struck vessel. In addition, the bulb fitting can be attached to the hull of the vessel with the possibility of its separation if there is a threat of collision between vessels. The following sections provide a detailed description of the proposed technical solutions and an analysis of their effectiveness. The proposed technical solutions have no analogs in world practice, which is confirmed by invention patents.

3. New Design Measures

In particular, this work proposes a design for a corrugated bulb, in the upper and lower parts of the corrugated walls there is a groove (Figure 1).

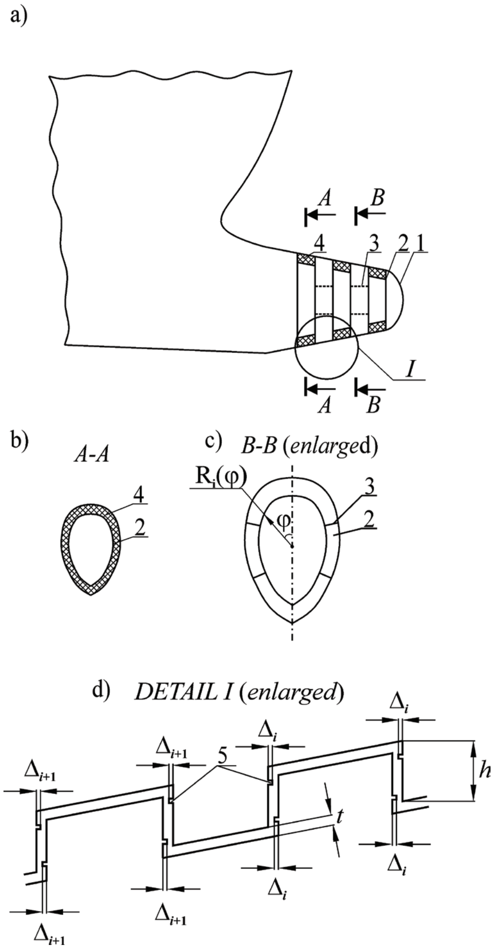

Figure 1. *Diagram of a corrugated bulb with grooves in the walls of the corrugations: a) general view; b) section A-A; c) section B-B; d) detail I; 1- fairing; 2- corrugated insert; 3- brackets; 4- elastic filler; 5- grooves*

To determine the relationship between the depth of the groove and the thickness and height of the corrugation at which the required compliance of the bulb fitting is ensured, plastic limit analysis can be used [22,23]. Let us consider the deformation of a corrugation with unit width b (Figure 2).

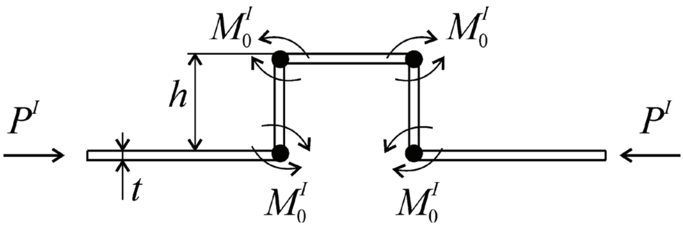

Figure 2. *Corrugation deformation diagram*

Limiting moment M_0^I of the section of a corr nit width b according to [22]

$$M_0^I = \sigma_T \cdot \frac{b \cdot t^2}{4} \quad (1)$$

where t – corrugation thickness, m;

b – corrugation width, m;

σ_T – yield strength of the corrugation material, Pa.

In this case, the ultimate load P^I leading to the folding of the corrugation can be determined within the framework of plastic limit analysis [22] as follows:

$$P^I \cdot h = 2 \cdot M_0^I \quad (2)$$

where h – corrugation height, m.

The limiting moment M_0^K for an annular corrugation can be determined by integrating (1) along the entire perimeter of the corrugation, considering the symmetry of the corrugation relative to the vertical plane

$$M_0^K = 2\int_0^{\pi} \frac{M_0^I}{b} \sqrt{[R'(\varphi)]^2 + [R(\varphi)]^2}\, d\varphi = \sigma_T \cdot \frac{t^2}{2} \int_0^{\pi} \sqrt{[R'(\varphi)]^2 + [R(\varphi)]^2}\, d\varphi \quad (3)$$

where $R(\varphi)$ – function describing the cross-sectional shape of the corrugation, m.

Equating the moment created by the force acting on the bulb fitting from the side of the side grillage at the moment of collision with the limiting moments acting at the vertices of the annular corrugation, in the absence of grooves, as in

$$P \cdot h = \sigma_T \cdot t^2 \int_0^{\pi} \sqrt{[R'(\varphi)]^2 + [R(\varphi)]^2}\, d\varphi \quad (4)$$

For a corrugation with grooves, condition (4) is transformed to

$$P \cdot h = \sigma_T \cdot (t - \Delta_i)^2 \int_0^{\pi} \sqrt{[R'(\varphi)]^2 + [R(\varphi)]^2}\, d\varphi \quad (5)$$

From this expression, we can determine the depth of the recess to determine the required compliance of the bulb

$$\Delta_i = t - \sqrt{\frac{h \cdot P_{0i}}{\sigma_T \cdot \int_0^{\pi} \sqrt{\left[R_i'(\varphi)\right]^2 + \left[R_i(\varphi)\right]^2}\, d\varphi}} \qquad (6)$$

where Δ_i is the depth of the recess of the *ith* corrugation, m;

h – corrugation height, m;

t – corrugation thickness, m;

P_{0i} – ultimate load of the ith corrugation, ensuring the required compliance of the bulb, *N*;

σ_T – yield strength of the corrugation material, Pa;

$R_i(\varphi)$ – function describing the cross-sectional shape of the ith corrugation, m.

Expression (6) was obtained within the framework of plastic limit analysis [22,23], according to which the deformation of the corrugations occurs with the formation of plastic hinges in their corners in the area where the grooves are located. The proposed design of the bulb fitting of the ship's hull (Figure 1) consists of a fairing 1, a corrugated insert 2, and brackets 3. The voids between the brackets installed on the outside are molded with elastic filler 4. In the upper and lower parts of the corrugation walls, grooves 5 of a certain depth are located [24].

In this technical solution, in the event of a ship collision, the deformation of the bulb begins with corrugations that have a minimum ultimate load that is regulated by changing the depth of the groove, thereby ensuring the required compliance of the bulb in the longitudinal direction.

In previously developed structures [20,21], the presence of an elastic filler increases the longitudinal rigidity of the bulb fitting because during its deformation during a ship collision, the outer edges of the corrugations begin to approach each other and clamp the elastic filler together, preventing it from being pushed out of the corrugation space.

This increases the force required to deform the bulb and prevents the reduction in the length of the bulb when the corrugations are deformed, which reduces the efficiency of using these structures.

This problem can be solved by installing elastic containers with a working medium in the voids between the surfaces of the corrugations and brackets instead of elastic filler [25], pressure relief devices in the walls of the corrugations, and shells on the outside (Figure 3).

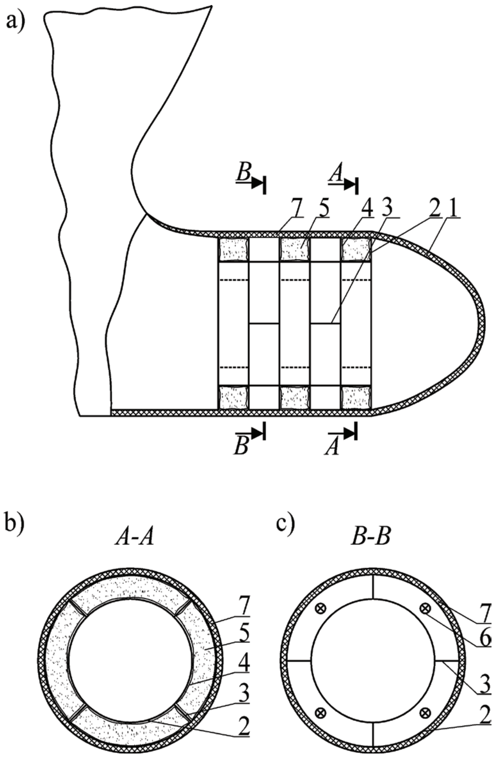

Figure 3. *Scheme of a corrugated bulb with elastic containers: a) general view; b) section A-A; c) section B-B; 1- fairing; 2- corrugated insert; 3- brackets; 4- elastic containers; 5- working medium; 6- pressure relief devices; 7- shell*

The proposed design of the bulb of the ship's hull consists of a fairing 1, a corrugated insert 2, and brackets 3. In the voids between the brackets, which are installed on the outside, there are elastic containers 4 with a working medium 5, and in the walls of the corrugations there are pressure relief devices 6. From the outside of the bulb insert, there is a shell 7.

When ships collide, the bulb comes into contact with the underwater part of the side framing system. In the above-water part, as the bulb is deformed, the upper part of the ship's stem comes into contact. Because the compliance in the longitudinal direction of the bulb is high, when ships collide, it is deformed with the formation of plastic hinges in the corners of the corrugated insert.

This is accompanied by an increase in pressure in the elastic containers and removal of the working medium using pressure relief devices that can be either safety valves or special structural elements that collapse when the pressure in the elastic containers exceeds a certain value.

The use of pressure relief devices would enable us removal of the working medium at a speed sufficient to allow unhindered deformation of the corrugated insert. Based on this condition, the number of pressure relief devices per elastic container must be selected considering its volume. Both liquid and gas under a certain pressure can be used as the working medium.

The shell located on the outer side of the structure improves the hydrodynamic characteristics of the bulb and does not prevent its deformation in case of collision, as it can be made of elastic materials such as rubber.

To achieve the necessary bulb compliance, it can also be designed in the form of separate sections. Their diameter increases toward the stern. The sections of the bulb must be fastened together, and the circular transverse frames must be attached to the shell plate with connecting elements. Their strength is determined by the given axial load on the bulb frame (Figure 4, where 1- shell plate; 2- circular transverse frame; 3- section of the bulb; 4- connecting element; 5- elastic shell).

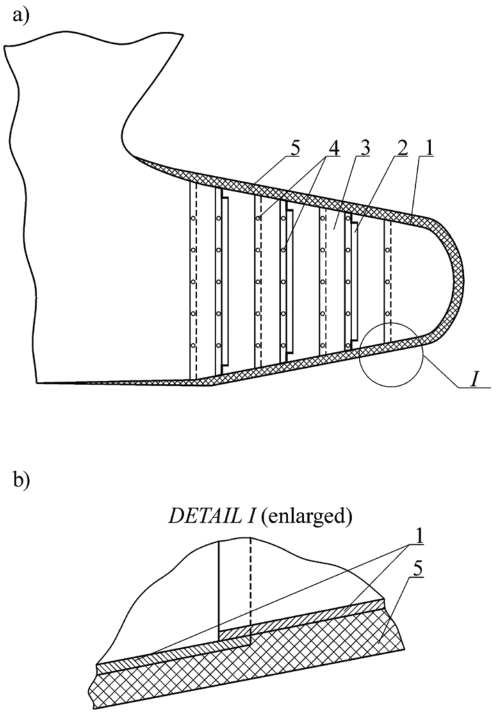

Figure 4. *Bulb with increased longitudinal compliance from individual sections: a) general view; b) detail I; 1-shell plate; 2- circular transverse frame; 3- section of the bulb; 4- connecting element; 5- elastic shell*

To ensure the required compliance, the number of connecting elements for each of the joints of the sections and the corresponding connections of the circular transverse frames should be determined using the following formula:

$$N_i = \frac{P_{0i}}{S \cdot \tau_B} \tag{7}$$

where P_{0i} is the maximum load of the ith connection of the sections of the bulb, ensuring the required compliance of the bulb, N;

N_i– number of connecting elements in the ith connection;

S– is the area of the connecting element, m^2;

τ_B– tensile strength of the material of the connecting element for shear, Pa.

In this technical solution [26], in case of a ship collision, the deformation of the bulb is carried out due to the cutting of the connecting elements and the movement of a section of the bulb with a minimum load limit of the connection inside the adjacent section of the bulb. The appropriate compliance of the bulb in the longitudinal direction can be ensured by the proper choice of the number of connecting elements, their cross-section, and material.

It is also possible to prevent the occurrence of underwater damage in the event of a collision by disconnecting the bulb of the striking vessel immediately before the collision. To achieve this, the bulb-shaped fairing should be secured to the ship's hull with adecision number: connection using explosive bolts (Figure 5). The proposed design consists of a casing 1, reinforced with stiffening ribs 4, and contains a bulb flange 2. Using explosive bolts 6 and nuts 7, the bulb flange 2 is attached to thedecision number: vessel hull flange 3, and gasket 5 is installed to seal the connection.

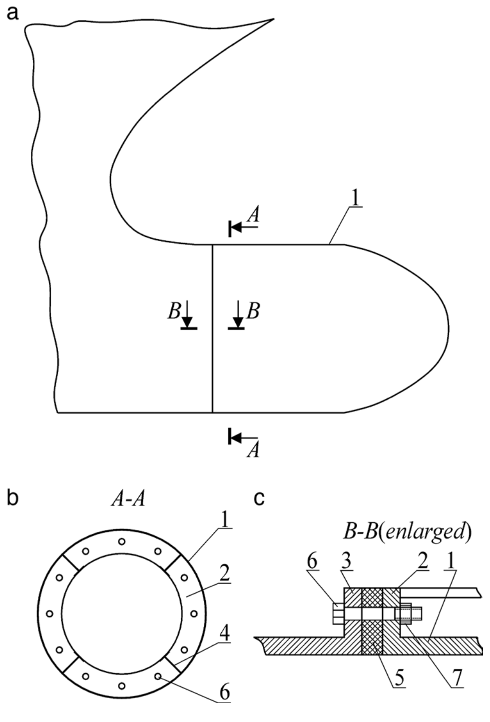

Figure 5. *Scheme of a detachable bulb: a) general view; b) section A-A; c) section B-B; 1- casing; 2- bulb flange; 3- vessel hull flange; 4- stiffening ribs; 5- gasket; 6- explosive bolts; 7- nuts*

If a danger of collision arises and it is impossible to avoid it by maneuvering, the explosive bolts connecting the bulbdecision number: to the ship's hull are undermined, which leads to the separation of the bulb and its flooding. In this case, during a collision, the upper part of the ship's stem comes into contact with the struck ship, resulting in deformation of the hull structures above the waterline. The command to detonate explosive bolts can be given either by the person steering the vessel or by the onboard intelligent system in automatic mode [27,28].

4. Analysis of the Effectiveness of the Developed Design Solutions

To evaluate the effectiveness of the developed design solutions, numerical modeling of the deformation of the bulbs of the proposed structures was performed using the ANSYS software package. Figure 6 shows a three-dimensional model of a bulb.

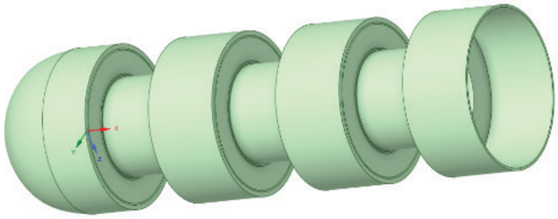

Figure 6. *Three-dimensional model of a corrugated bulb with grooves*

Figure 7 shows a bulb during the deformation process and the distribution of plastic deformations under bulb loading.

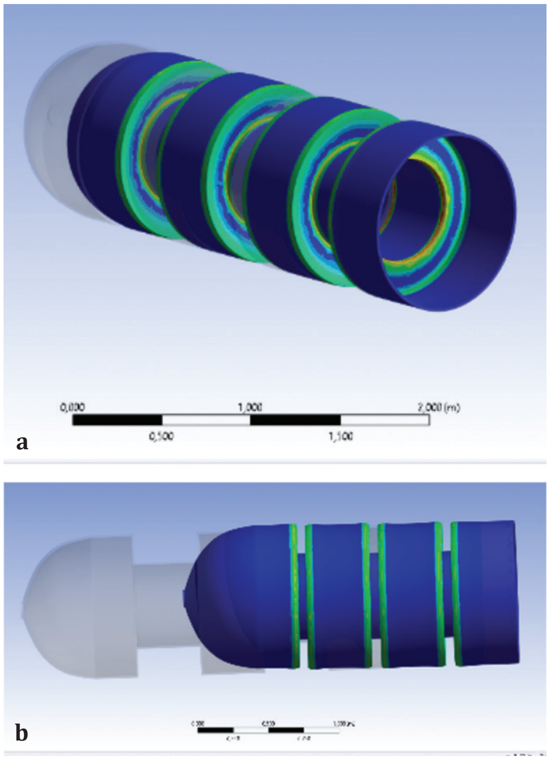

Figure 7. *Distribution of plastic deformations upon loading the bulb*

It can be seen that plastic deformations are concentrated in the area of corrugation corners, which confirms the advisability of using the plastic limit analysis when determining the load-bearing capacity of corrugated bulbs.

As the study has shown, formulas of the form (6), obtained using methods of plastic limit analysis [22,23], can be used to assess the load-bearing capacity of corrugated bulb structures of the proposed design.

To confirm the effectiveness of the proposed design solutions, a simulation of the process of interaction between the bulb structure and the side grillage of the struck vessel was performed using ANSYS LS-DYNA software. The thickness of the plating of the bulb fittings of the proposed and traditional designs was assumed to be the same and equal to 16 mm. Models of the bulb fitting and the side grillage before the start of testing are presented in Figure 8, and the results are presented in Figure 9. It can be seen that until the bulb is almost completely folded, the deformations of the side grillage of the struck vessel do not exceed 0.5 m, whereas destruction of the side floor does not occur. The highest stresses in the beam of the side floor of the struck vessel are approximately 512 MPa.

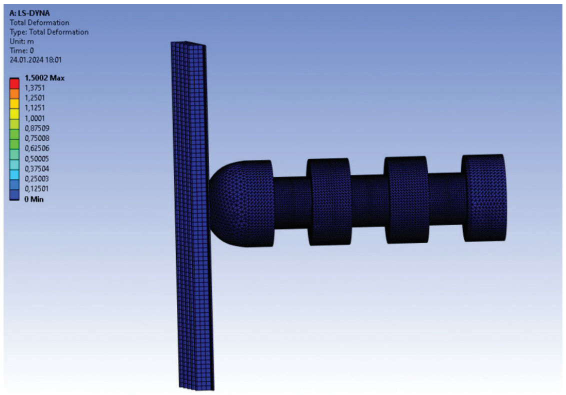

Figure 8. *Models of the side grillage and bulb of the proposed design before testing*

Figure 10 shows the results of the interaction between a traditional bulb structure and a side grillage. It can be seen that the bow bulb remains practically free of distortion, the deformation of the side grillage is 0.75 m, and the stress is 560 MPa, while a collapse of the side grillage set is observed. With further impact of the bulb fitting on the side grillage, its destruction is observed.

The nature of the interaction between a traditional bulb structure and a side grillage obtained as a result of a computational experiment is in good compliance with the data of [1,3,5,6].

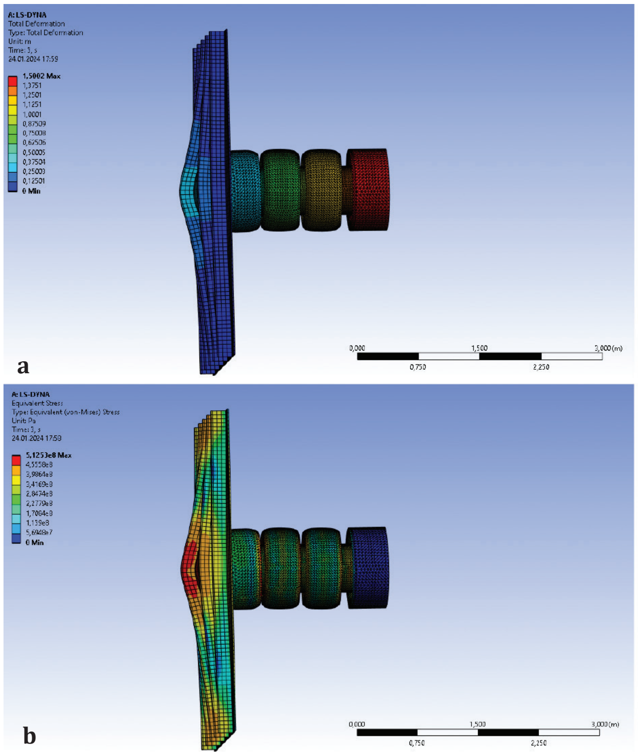

Figure 9. *Results of modeling the collision process when using the bulb of the proposed design: a) deformation; b) stress*

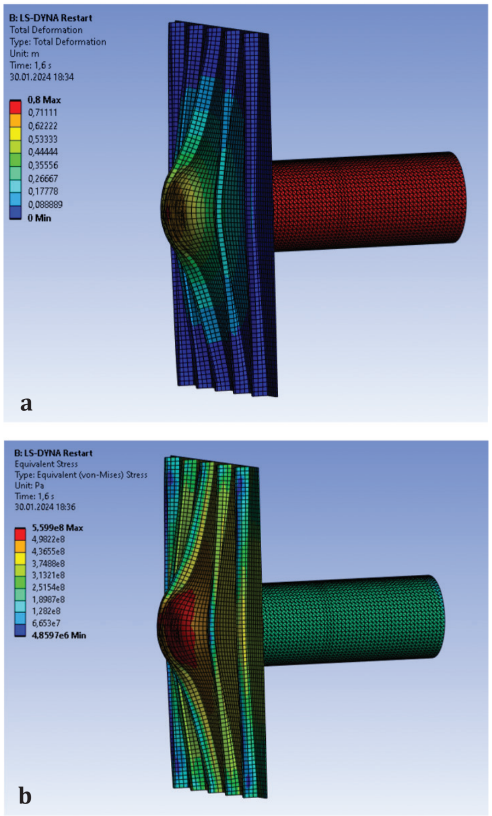

Figure 10. *Results of modeling the collision process when using a traditional bulb design: a) deformation; b) stress*

5. Discussion

As the study showed, the use of bow bulbs with increased longitudinal compliance can significantly reduce the deformation of the side grillage of a struck vessel, preventing its destruction and leakage of transported cargo, which is especially important for tankers. The obtained result complies with the results of the studies presented in [5,6,18].

The use of the design solutions proposed in this work makes it possible to implement the concept of a flexible bow extremity [14]. In this case, energy dissipation during the implementation of the proposed design must be carried out mainly because of the deformation of the hull in the above-water part. A similar approach was proposed earlier in [29], and the bulb design presented there was constructed with non-tight shells and stiffened with vertical ring frames to reduce the axial crushing rigidity to a minimal level.

Note that in the case of implementing structures [24,25], it is possible to increase the amount of energy dissipated during bulb deformation by changing the height and number of corrugations. In this case, the required compliance of the bulb will be maintained because of the appropriate choice of the thickness of the corrugations and the depth of the recesses. The design presented in [26], compared to [24,25], has a lower energy intensity, and to increase it, additional deformable elements made of material with relatively low strength characteristics can be placed in the inner part of the bulb fitting. In this case, after cutting the connecting elements, the load during bulb deformation will not increase, and the energy intensity will increase.

If the design presented in Figure 4 is implemented, energy dissipation will occur only due to the deformation of the above-water part of the hull. In this case, it is necessary to make the above-water part of the vessel with increased longitudinal compliance, as proposed in [16].

6. Conclusion

Based on the results of the research, schemes for modernizing the forward end of ship hulls by installing bulbs with increased longitudinal compliance to reduce the consequences of ship collisions were proposed, and recommendations were developed for the selection of their characteristics, which make it possible to avoid underwater holes on a struck ship. The developed technical solutions ensure that in case of collision in the underwater part of a struck vessel, the deformations of the framing systems will remain insignificant, thereby avoiding the appearance of damage below the waterline. Thus, it seems possible to avoid a ship wreck and crew losses, environmental pollution, and significantly decrease the amount of repairs due to reduced damage to the hull in case of collision. The relevance of the proposed design solutions is proved by invention patents; their implementation into repair and ship hull modernization will significantly reduce the damage from navigation accidents. Conducting further research in this direction must include a design study of the proposed technical solutions in relation to specific ship designs for subsequent trial operations.

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