

DEVELOPMENT OF A COMPOSITE HATCH COVER

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Abstract. Two designs of a composite marine hatch cover were developed on the basis of the design of a steel one. One of the proposed designs features composite structure made by means of manual lay-up technology, and the other one is based on a truss composite structure which can be produced by rod winding process. Selection of the most rational materials and design parameters was carried out on the basis of finite element simulations and use of parametric optimization methods. Results reveal the possibility of weight reduction by means of using composites in the hatch cover, which is associated, however, with a comparatively high cost.

Keywords: composite material, finite element analysis, hatch cover, parametric optimization, sandwich panel

1. Introduction

Steel structures are still widely used nowadays. Nevertheless, some industries require less conventional and more complex materials, such as composites, due to their outstanding properties. Composite materials have a wide range of advantages over conventional materials such as high strength-to-weight ratio, good chemical, and fatigue resistance. At the same time, there are also a number of problems limiting their practical application and preventing them from becoming ubiquitous. The most frequently mentioned shortcomings are high price, problems in connection with metals due to differences in physical and mechanical properties, toxicity of some materials, and the release of combustion products upon ignition, in some cases – insufficient plasticity and brittle fracture [1-3]. Nevertheless, the use of composite materials in various industries becomes increasingly popular. In addition to the possibility of improvement of product characteristics, the utilization of composites has a positive influence on a company's reputation, shows its technological capabilities and a modern approach to production, the desire to develop and keep pace with the times. As a result, composite manufacturing has become a global trend over the last few decades in many industries.

Hatch cover is an element of a vessel designed to ensure safe and sealed storage of goods during transportation. Despite the fact that hatch covers are not among main load-carrying elements of the hull, their strength and stiffness characteristics have to meet the requirements in accordance with adopted rules and regulations. The design of hatch cover which satisfies these requirements ensures normal operation of a vessel, safety of its crew, and integrity of a cargo.

In shipbuilding, composite materials (carbon fiber-reinforced plastics (CFRP) and glass-reinforced plastics (GRP)) have been used since the mid-20th. In 1958 Henri Jeanneau, the founder of a famous French shipyard and company of the same name, created the first hull of a yacht made of GRP [4], which was a real technological breakthrough of that time.

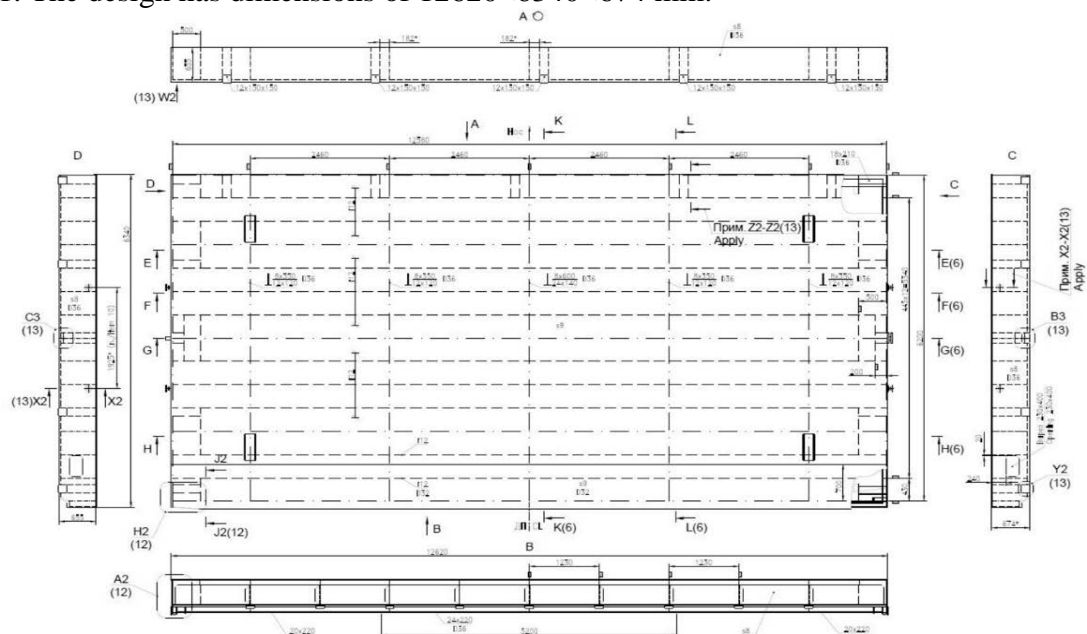
First norms defining the rules of design and strength assessment of composite components appeared much later. For example, international accredited registrar and classification society Det Norske Veritas and Germanischer Lloyd (DNV GL) issued such document in January 2003 (Composite Components, DNV-OS-C501). The set of regulations of the Russian Maritime Register of Shipping (version 2018) also provides a number of documents defining the development of composite parts (Rules for the Classification and Construction of Sea-Going Ships 2018, Part XIII - Materials; Load Line Rules for Sea-Going Ships, etc.).

There are plenty of studies on implementation of composite materials in shipbuilding. At the same time, only a few of them concern hatch covers. Jun Li et al. [5] compared strength, mass, and economic characteristics of a conventional steel hatch cover and a composite one of the 230,000 DWT ore carrier. Basem E. Tawfik et al. [6] conducted a similar study for hatch covers of a middle size bulk carrier. Weight reduction approach and strengthening approach are discussed in the article. K. Kunal et al. [7] used four different laminates in a design of a hatch cover. All authors in [5-7] suggested structures made of laminates and concluded the feasibility of producing a composite hatch cover. Li Kai et al. [8] developed a multi-level optimization algorithm, based on an improved bidirectional evolutionary structural optimization (BESO) method and surrogate model method, and applied it to design a steel hatch cover with irregular pattern of its ribs of the 180,000 DWT bulk carrier.

The purpose of this work is to develop a composite version of a hatch cover, to select a binder and fabric (the constituents of a composite material), to reduce the weight of the structure due to the optimal choice of its wall thickness, and to compare characteristics of the composite version with those of the original steel one. Significant attention is paid to parametric design optimization. In addition, the article proposes an alternative innovative method of manufacturing a hatch cover using a rod winding process. The work described in the article was carried out as a result of collaborated research of specialists of Peter the Great St. Petersburg Polytechnic University and BaltiCo GmbH.

2. Description of the hatch cover design and solution stages

The drawing of original steel version hatch cover of the dry cargo vessel RSD59 is shown in Fig. 1. The design has dimensions of 12620×6340×674 mm.



Original composite design (sandwich structure). The initial version of a composite analogue is presented in Fig. 2.

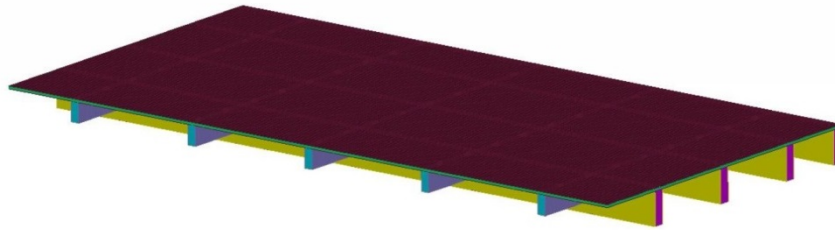


Fig. 2. Design of a composite analogue of a steel hatch cover

The composite design of hatch cover consists of a hatch plating, as well as principal direction beams (PDB) and crossbeams (CB). The initial composite structure includes five PDBs and four CBs. The hatch plating is an element of «sandwich» type, i.e. it consists of two external rigid casings and a low-density core between them. The PDBs and CBs also have a sandwich structure or are hollow. Fabric in the casings is laid so that its principal directions are parallel or perpendicular to the sides of beams and hatch plating.

The overall problem of a composite hatch cover development was roughly divided into five stages:

1. Selection of materials that are the most rational for manufacturing of the hatch plating, PDBs, and CBs;
2. Selection of thicknesses of the hatch plating's and beams' casings for an initial version of the composite structure (5 PDBs, 4 CBs);
3. Reconfiguration of PDBs and CBs arrangement, reselection of casing thicknesses;
4. Selection of the most rational version of hatch cover design based on the conducted calculations;
5. Clarification of design parameters by taking into account forming layers at the points where the beams are connected to each other and to the hatch plating.

Most of the subtasks listed above are solved using numerical methods. The finite element method is used to analyze the stress-strain state of the hatch cover. Parametric optimization algorithms are used to find the most rational design variables.

It is worth noting that stages 1, 2, and 3 can be combined into one subtask of parametric optimization, but such decision leads to a significant complication of the mathematical model and, consequently, requires an increase in computational resources. Only the first 4 stages of general problem are considered in this work, while a separate study is supposed to be devoted to a modeling of forming layers. However, it can be assumed that the optimal design parameters found in the first 4 stages should not significantly change their values at stage 5.

Alternative design of the truss structure based on the RP-technology (developed in BaltiCo GmbH). Alternatively, we suggest the following hatch cover with the truss structure which was developed in BaltiCo GmbH (Rostock, Germany).

The main feature of this structure is that it is produced using the rod winding process – a novel process for production of the structures made of high-performance composite materials. The process has been developed and tested in recent years at BaltiCo GmbH in cooperation with well-known research institutions such as the Fraunhofer Institute and the University of Rostock. It enables a completely new quality for components made of fiber composites.

In the bar winding process, roving strands impregnated with resin and made up of fibers are deposited at nodal points. They form complex two- and three-dimensional supporting

construction with a high level of lightweight construction potential. The laying process is carried out fully automatically via a specially developed robot system and minimizes manual activities. This benefits a high and reproducible quality. The model of such structure is shown in Fig. 3. The composite design of the hatch cover, suggested in the paper, consists of a top (red in Fig. 3), side hatch plating (green), transverse ribs (yellow), and carbon truss structure (Fig. 4). The design of laminates is given in Table 1.

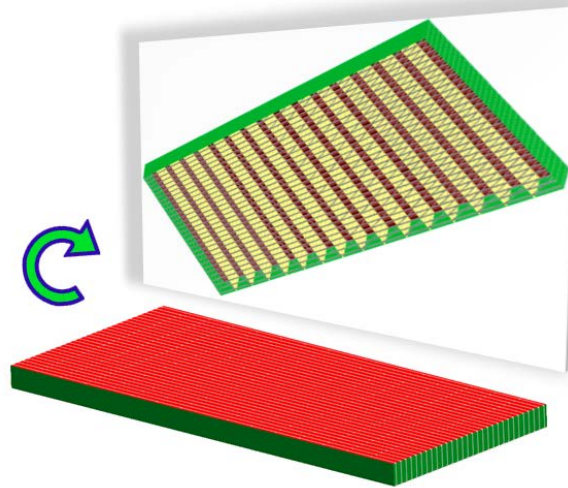


Fig. 3. Design of the hatch cover with truss structure

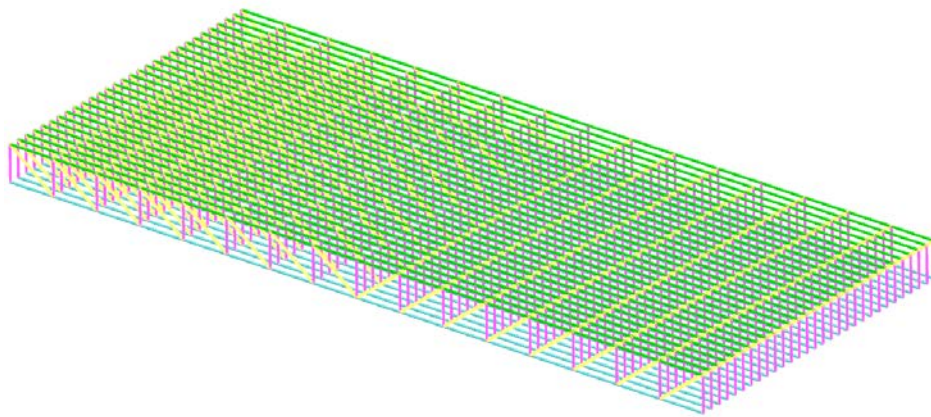


Fig. 4. Colour scheme of the truss structure (green – top longitudinal rods, pink – vertical rods, yellow – diagonal rods, blue – bottom longitudinal rods)

Truss structure consists of the following rods made of carbon rovings with epoxy-matrix:

- top longitudinal rods (green in Fig. 4; radius is 21.8 mm), which go right under the plating;
- vertical rods (pink; radius is 21.8 mm), which are glued to the ribs;
- diagonal rods (yellow; radius is 11.65 mm), which connect the bottom edges of the rib and top edge of the next ribs;
- bottom longitudinal rods (blue; radius is 22.73 mm), which are parallel to the top rods and connect the bottom edges of the ribs.

Table 1. Combinations of materials for the elements of the truss structure

| Element | Layer | Thickness, mm | Material |
|--------------------|-------|---------------|---------------|
| Top hatch plating | 1 | 4 | GRP fabric QX |
| | 2 | 20 | Foam |
| | 3 | 4 | GRP fabric QX |
| Side hatch plating | 1 | 4 | GRP fabric QX |
| | 2 | 5 | Foam |
| | 3 | 4 | GRP fabric QX |
| Transverse ribs | 1 | 2 | GRP fabric QX |
| | 2 | 10 | Sandwich-foam |
| | 3 | 2 | GRP fabric QX |

3. Loads, boundary conditions, constraints

The loads that the design of hatch cover has to withstand were determined according to the rules of the Russian Maritime Register of Shipping (version 2018) [9]. According to the regulatory documents, the design load distributed on the hatch plating surface is 3.5 t/m². The hatch cover is considered to be freely supported on three sides of the hatch plating. It is supposed that the beams are perfectly connected mechanically with each other and with the plating, the honeycomb core – with the casings of the sandwich panel, and the neighbor layers of fabric in the casings – with each other. Development of a composite version of the steel hatch cover is carried out taking into account the requirements of the Russian Maritime Register of Shipping for stiffness and strength of the structure. In particular, the maximum deflection of the structure must not exceed 70.4 mm, and the strength of the hatch cover must be ensured taking into account the safety factor of 3.3. In addition, there is a technological constraint of 30 mm on the maximum value of the thickness of the composite casing. Strength of the composite casings is estimated using the criterion of maximum stresses [1]:

$$\xi = \max \left\{ \begin{array}{l} \frac{\sigma_{XT}}{\sigma_{XT}^f} \text{ or } \frac{\sigma_{XC}}{\sigma_{XC}^f} \\ \frac{\sigma_{YT}}{\sigma_{YT}^f} \text{ or } \frac{\sigma_{YC}}{\sigma_{YC}^f} \\ \frac{|\sigma_{XY}|}{\sigma_{XY}^f} \end{array} \right. \quad (1)$$

Here σ_{XT}^f , σ_{YT}^f (σ_{XC}^f , σ_{YC}^f) are ultimate tensile (compressive) strength in the casing layer in the directions along and across fibers respectively; σ_{XY}^f is the shear strength of the layer in its plane; σ_{XT} , σ_{YT} (σ_{XC} , σ_{YC}), σ_{XY} are the components of the stress tensor which are found regarding the same coordinate system as the layer ultimate strengths specified above. The value of $\xi \geq 0.3$ (bearing in mind the safety factor) corresponds to the compliance of the failure criterion.

It should be noted that the structural strength is not estimated at the points of beam connections and at the regions where the boundary conditions are imposed on the hatch plating in numerical parametric optimization process. In the first case that is permissible due to the omission of forming layers, which would have reduced the effect of stress concentration, and in the second case - due to the rigid fixation of hatch plating boundaries in the FE model.

4. Results and discussion. Original composite design (sandwich structure)

Material selection and thickness optimization of the original composite hatch cover (sandwich structure). In order to select the material that would be the most rational choice for manufacturing of the composite hatch cover, seven tasks of single-objective parametric optimization with constraints were solved.

Optimization variables are five thicknesses that are shown in Fig. 5. The objective function of the parametric optimization processes is the minimization of the mass of the composite hatch cover. Constraints on the maximum deflection, strength, and maximum technological thickness of the casings are given in the previous section.

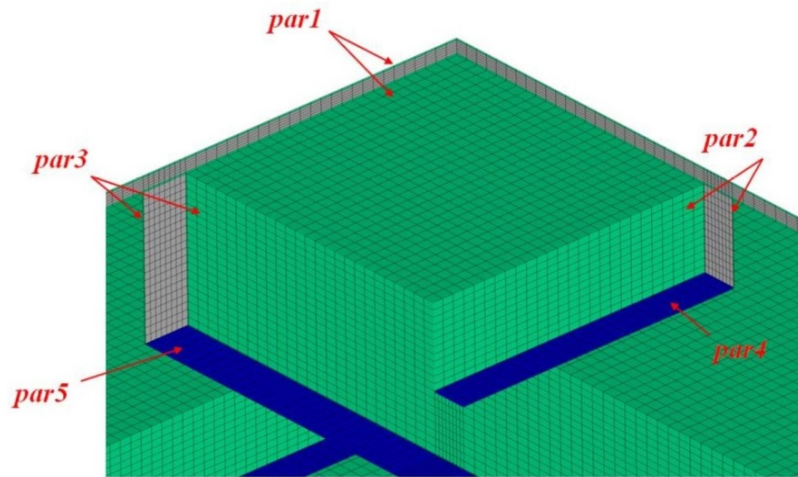


Fig. 5. Optimization design variables

The complete list of all considered combinations of the materials is provided in Table 2. Physical and mechanical characteristics of these materials were defined from specimen testing or found in GRANTA Mi [[10], [11]] – a large database of material properties. Only elastic behavior of the materials is considered in the framework of this work.

Table 2. Combinations of the materials for the hatch cover design

| Option # | PDBs' and CBs' core | Casings of PDBs, CBs and hatch platings | Hatch plating's core |
|----------|---------------------|---|----------------------|
| 1 | Styrofoam | GRP fabric | Styrofoam |
| 2 | – | GRP fabric | CFRP honeycomb core |
| 3 | – | GRP fabric | PP honeycomb core |
| 4 | – | CFRP fabric | CFRP honeycomb core |
| 5 | – | CFRP fabric | PP honeycomb core |
| 6 | – | CFRP fabric | Styrofoam |
| 7 | – | CFRP fabric | GRP honeycomb core |

Optimization problems were solved by use of the genetic algorithm MOGA-II. The thicknesses were varied with the increment 0.5 mm. Two hundreds of iterations were made for each set of materials from Table 2.

Calculation results have shown the impossibility of parameter selection that would satisfy the technological requirement for maximum thickness of GPR and CFRP casings, as well as the constraints on strength and stiffness of the structure. However, analysis of the

results has identified two combinations of the materials which are considered to be the best ones. Combination #4 is the best one from the strength and stiffness standpoints. However, the CFRP honeycomb core used in this option has a high cost that can make the manufacture of the composite hatch cover economically unfeasible. Therefore, option #7, which is characterized by a good combination of strength/stiffness and cost performance, was selected to be used for further calculations.

Modification of beam configuration. In order to increase the bending stiffness of the composite hatch cover, the initial configuration of beams (5 PDBs, 4 CBs) was changed by increasing the number of CBs and reducing the number of PDBs accordingly (Fig. 6).

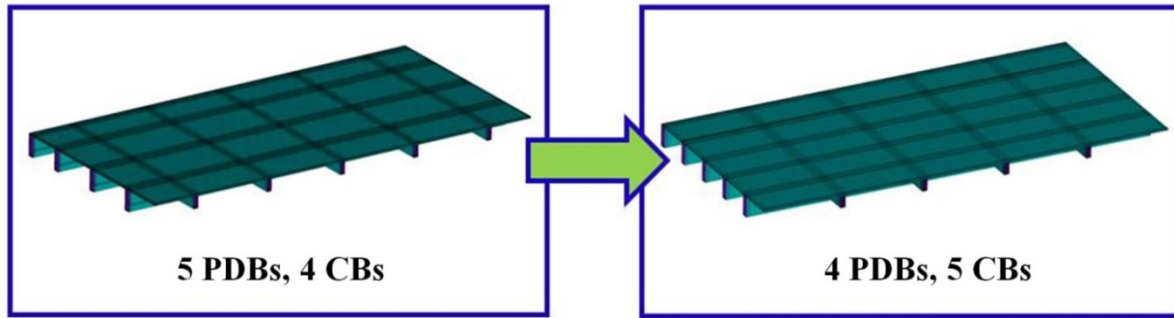


Fig. 6. FE model of the composite hatch cover with the modified beam configuration

As mentioned previously, further calculations were made for two combinations of materials – #4 and #7, which differ in type of honeycomb core (CFRP and GRP respectively).

The most rational thickness values obtained for the modified beam configuration of the composite hatch cover by means of parametric optimization are given in Table 3. Genetic algorithm MOGA-II included 20 populations with 20 points for each combination of the materials (400 iterations).

Table 3. The most rational versions of composite hatch cover design with the modified beam configuration

| Option # | par1, mm | par2, mm | par3, mm | par4, mm | par5, mm | M, kg | U, mm | ξ |
|----------|----------|----------|----------|----------|----------|--------|-------|-------|
| 4 | 5.0 | 5.0 | 26.5 | 8.5 | 28.5 | 7537.6 | 69.31 | 0.221 |
| 4A | 13.5 | 2.5 | 28.0 | 13.0 | 30.0 | 7336.7 | 69.83 | 0.294 |
| 7 | 13.5 | 2.5 | 28.0 | 13.0 | 30.0 | 7336.7 | 70.02 | 0.297 |

The new configuration of beam arrangement together with the material choice made it possible to satisfy all the constraints imposed. Comparing the results for CFRP and GRP honeycomb cores it should be noted that in the latter case the solution with a smaller value of mass was received.

However, the results of the first step have shown that CFRP honeycomb core is preferred in terms of both stiffness and strength. In this way, since the optimization algorithm could miss the area of truly optimal parameters, it was decided to apply the most rational values of thickness obtained for the structure with GRP honeycombs (option #7, see Table 3) to the structure with CFRP honeycombs (option #4A). Hatch cover #4A has better strength and stiffness characteristics than #7, whereas the mass is the same. Nevertheless, since the use of the expensive CFRP honeycomb core didn't lead to significant benefits over the GRP core, the decision was made to consider the GRP honeycombs and the design #7 as the most appropriate combination. The deformed state of the hatch cover #7 is shown in Fig. 8.

The next stage of the design modification concerned increasing the height of the PDBs to the level of the CBs (Fig. 7).

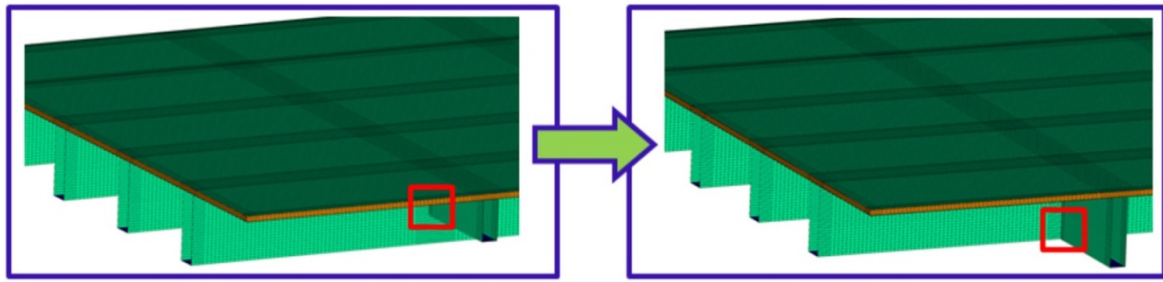


Fig. 7. Composite hatch cover of modified beam configuration and increased height of PDBs

Calculations were performed for the material combination #7 only. The most rational solution (#7A) obtained for this design during the optimization process is shown in Table 4. It also shows the output characteristics of the structure (#4B) with the same PDBs' and CBs' height and thickness parameters corresponding to the hatch cover #4A.

The increase in the height of the PDBs didn't lead to any improvement in the results. It can be explained by the fact that high PDBs don't allow to redistribute the load on the whole hatch including the uttermost CB. Consequently, the latter doesn't experience additional rotation around its axis. This explains the difference in the deformed state between structures with high and low PDBs (see Fig. 8).

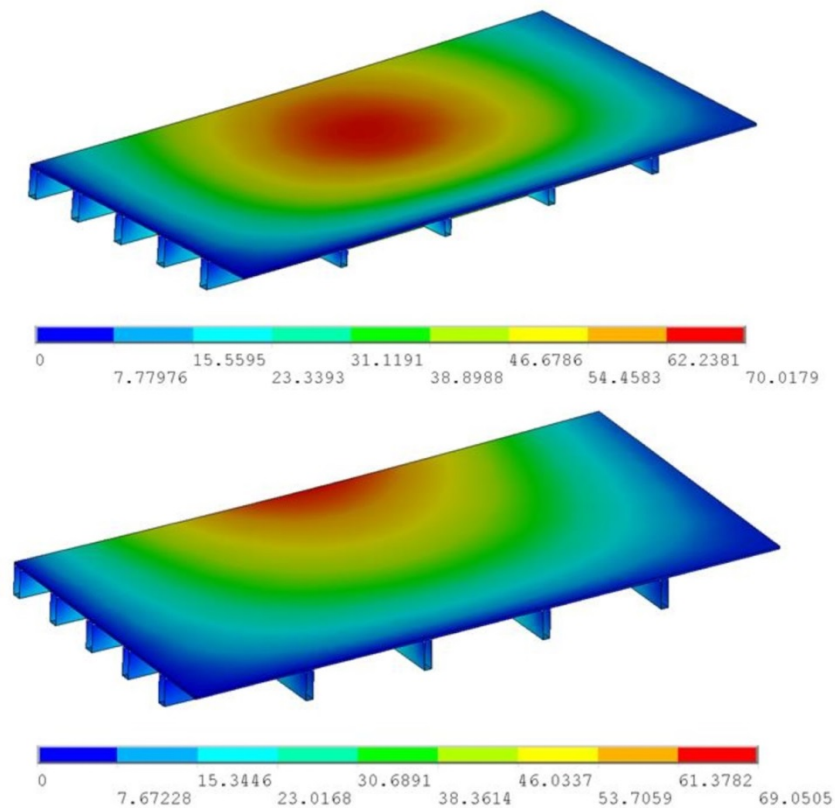


Fig. 8. Deformed state of the hatch covers #7 (top) and #7A (bottom)

Table 4. The most rational versions of composite hatch cover design with modified beam configuration and increased height of PDBs

| Option # | par1, mm | par2, mm | par3, mm | par4, mm | par5, mm | M, kg | U, mm | Ξ |
|----------|-------------|-------------|-------------|-------------|-------------|--------|-------|-------|
| 7A | 17.0 | 4.5 | 30.0 | 28.5 | 29.5 | 8619.2 | 69.05 | 0.290 |
| 4B | 13.5 | 2.5 | 28.0 | 13.0 | 30.0 | 7377.7 | 73.51 | 0.452 |

Estimation of the production cost. An estimation of the feasibility of composite hatch cover manufacture should be carried out primarily in comparison with the steel one. The mass of the steel hatch cover according to drawings is about 12 tons. The minimum mass of the composite structure (#4 and #7) obtained in calculations is 7336.7 kg. This value is underestimated due to neglecting forming layers in the framework of this work. Further, a rough assessment of the production cost is made for both structures.

Using the data from the web let's accept the average price of 1 ton of rolled metal products equal to 50 thousand rubles (€715). Therefore, the cost of material needed for production of one steel hatch cover is 600 thousand rubles (€600). Assuming that the cost of material is 43% of the total cost of production of metal structure [5], we obtain the following cost of the design unit: 1 million 395 thousand rubles (€19930).

In order to use the same method for the cost assessment of the composite hatch cover, we also utilized the data provided in work [6]. Let's accept that the cost of material needed for the production of one composite hatch cover by manual lay-up technology is 31% of the total cost. The price of GRP honeycomb core is 3.5 thousand rubles (€50) per square meter, and the price of CFRP honeycombs is 43 thousand rubles (€615) per square meter. The hatch plating has a size of 12620×6340 mm, and the height of sandwich core is 50 mm. According to the technological restrictions provided by the manufacturer, the maximum possible size of sandwich core panels is equal to 1200×2500×27 mm. On this basis, 56 panels are required to manufacture the hatch plating. The cost of the hatch plating sandwich core material, therefore, is 590 thousand rubles (€8430) and 7 million 224 thousand rubles (€103200) for GRP and CFRP honeycombs respectively. In view of the cost factor, the decision to refuse from CFRP honeycombs seems obvious. Assuming the average price of a bidirectional CFRP fabric equal to 2 thousand rubles per square meter and thickness of one layer equal to 1 mm, the estimated cost of materials for the hatch cover composite casings according to design #7 is 9 million 480 thousand rubles (€135430).

The fiber volume fraction in the used composites is 50%. Impregnation of composite casings requires 2.5 m³ of polymer binder (epoxy resin). Assuming the price of polymer binder equal to 250 rubles (€3.6) per kilogram and the density of epoxy equal to 1250 kg/m³, the estimated costs of epoxy resin is 780 thousand rubles (€1150).

To sum up, the total cost of all necessary materials equals to 10 million 850 thousand rubles (€155000), and the cost of production of one composite hatch cover can be estimated as 35 million rubles (5€00000).

The provided calculation of the cost of production of hatch covers is approximate and contains many assumptions; nevertheless, it allows drawing some conclusions. It is obvious that the composite hatch cover is significantly more expensive to produce than the metal one. However, even with the significant difference in cost, the composite structure is able to make a profit in the future by allowing more cargo to be carried on a board of a vessel due to its lower weight.

5. Results and discussion. Alternative composite design (truss structure)

Results of FE modeling. FE analysis with the same load cases was conducted. The maximum displacement of the structure is 69.54 mm (see Fig. 9) that is less than maximum allowable 70.4 mm, while the value of ξ is 0.22.

Estimation of the production cost. Approximate mass of the alternative composite structure is 4886 kg. Based on the high level of the manufacturing automation we assume that the cost of material required for the production of one composite hatch cover is 31% of the total cost. The price of glass fiber is 1.5 euro per cubic meter, and the estimated volume of glass required for manufacturing of the required GFRP is about 0.55 m³ (1430 kg; 50% volume fraction considered). That leads to the cost of glass fiber required about €145 (1.5€/kg).

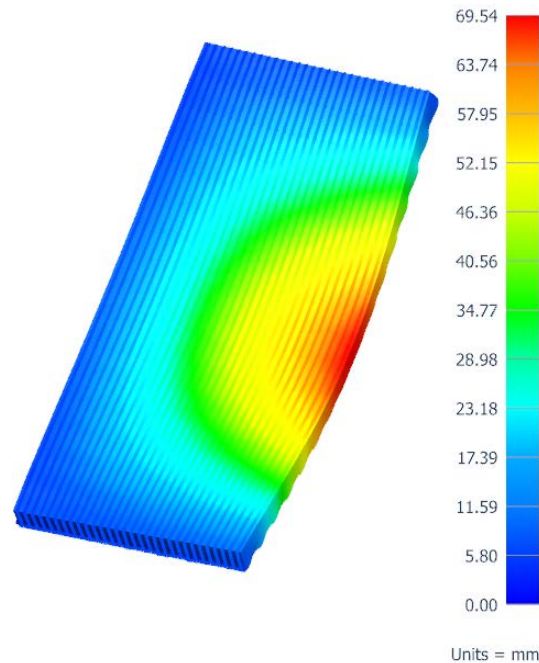


Fig. 9. Displacement field of the alternative hatch structure

The most expensive part of this construction is the rovings made of carbon fibers, 0.62 m³ of which (1099 kg; 35% fiber volume fraction considered) is required for the rod winding process. The estimated cost is €15390 (14€/kg). As it was shown in Tables 4-6, the sandwich structure includes the foam of various thickness: 5 mm foam costs approximately 25€/m², 10 mm – 35€/m², 20 mm – 60€/m². Approximately 25 m² of 5 mm foam, 60 m² of 10 mm foam, and 80 m² of 20 mm foam cost together about €7525.

Taking into account the fiber volume fractions of the GFRP and carbon truss structures, one can calculate the total volume of the epoxy needed for manufacturing – 1.70 m³. Considering the density of 1050 kg/m³ we get the mass of 1785 kg, which yields its cost of €8905. To sum up, total cost of all necessary materials equals approximately €34000, and the cost of production of one composite hatch cover with the truss structure can be estimated as €110000.

6. Conclusions

This work was focused on the development of a composite version of the hatch cover design. The general approach to the solution of the problem has been proposed, the necessary calculations have been carried out, as well as the assessment of the economic expediency of the production of composite hatch covers has been made as a result of conducted study. The weight of the structure was reduced by 4.5 tons in comparison with the steel hatch cover.

An alternative design of the hatch cover with truss structure having the weight 7.1 tons lower than that of the steel one was proposed. Manufacturing cost was estimated for both composite designs – both were found to be more expensive than the steel hatch cover, but the alternative approach was found to be cheaper than the conventional composite design based on sandwich structure. However, it should be taken into consideration that the difference of these costs is to some extent caused by the different countries where the production was supposed to take place (prices for raw materials can be significantly different as well as hourly labour costs). Cost of clamps and connectors was not taken into account in estimation of the hatch cover manufacturing cost for either design.

It is worth noting that usually there are plenty of hatch covers in a vessel. A decrease in mass of each of them, therefore, helps to carry significantly more goods. The designs of the composite hatch cover obtained in the work were found to be the most rational from the considered ones, but should not be referred to as final ones. Further examination of mutual location of the stiffeners and their dimensions may lead to improvement of characteristics of the hatch cover.

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