RESEARCH ARTICLE

Development of the ship hull assembly sub-process

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Objective: The development of the ship hull assembly process is possible by changing the method of assembly of basic parts at the building site, which would shorten the duration of the process and lead to cost reduction. One of the possibilities is to increase the dimensions and mass of basic building units, as well as the crane capacity at the building site.

Methods: Ship hull assembly methods involving sections, blocks and modules are used in the hull assembly phase. In the world's best shipyards, ships are built from blocks or modules, in which as much equipment as possible is installed. This paper uses the finite element method (FEM) for structural analysis, and its results serve to define the optimal technological instructions for the vertical transport of ship hull structure blocks.

Results: The development of the ship hull assembly sub-process can be achieved by using the hull block assembly method instead of the hull section assembly method. For the ship presented in this paper, the mass of a block transported to the building site was increased 3 times, so the number of building units was reduced by 65%. This reduces transport activities on the building site and shortens the duration of the assembly process by 20%. This paper shows that strengthening the block structure with temporary stiffeners is necessary for safe transport. It is possible to optimize their number and layout by using structural analysis.

Conclusion: The development of numerical finite element methods, software packages, and computers allow wider use of structural analysis in solving engineering problems in shipbuilding technology. The simulation of realistic situations, a wide range of analyses and a large number of results become possible, and they raise the level of knowledge and enable better decision-making in the production process.

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Introduction

The shipbuilding production process is complex and time-consuming. A large amount of materials and information goes through the process, and this is accompanied by a significant consumption of work resources, energy, and money. Shipyards can remain on the world market only if they adhere to the conditions of competition such as attractive projects, low prices, good quality, and short product delivery times, so reducing production costs and shortening production cycles is crucial (Sladoljev, 1995). Complex technological processes such as the shipbuilding process need to be carefully managed and must be divided into several sub-processes for that to be possible. Considered separately, each sub-process forms a whole, but is highly dependent on other sub-processes. In the shipbuilding technological process, these are the production of structural elements and equipment, structure and equipment pre-assembly, ship hull assembly, as well as final fitting out, testing, and handover (Zaplatić, 2009). Each sub-process must be constantly analyzed and developed along with the entire shipbuilding process.

The development of the ship hull assembly process is possible by changing the building method, which includes increasing the dimensions and mass of basic building components (Storch, Hammon, Bunch, & Moore, 1995). Structural blocks with a mass of up to 500 t become basic building units instead of 200 t sections (Brodosplit, 2020). In this respect, it is essential to increase crane capacities at the building site. The increase in dimensions and masses of basic building units and crane capacities at the building site affects all previous phases of the shipbuilding production process, so it is necessary to detect and analyze critical activities.

Defining safe vertical transport of hull structure blocks to the building site is one of the issues that arise. Transport of structures with large dimensions and masses must be safe for all employees, and this is achieved by installing lugs for safe vertical transport, as well as by installing temporary stiffeners on the blocks. The number and geometric characteristics of temporary stiffeners in the observed shipyard are defined empirically.

Using advanced numerical finite element methods and software packages, complex shipbuilding tasks can be modeled on a computer, various scenarios can be simulated, and valuable data for reasoned decision-making can be obtained by analyzing the results of calculations.

This paper presents the modeling and simulation of various scenarios of vertical transport of ship hull block structures. The results of the analysis are calculated values of structural strains and stresses that serve to define vertical transport parameters and the development of optimal technological instructions.

Methods

This article presents the methods used for ship hull assembly at a building site. Changing the assembly method in the shipyard reduces the duration of the shipbuilding process and costs, and it affects the entire production process. Some aspects can be analyzed using the numerical finite element method (FEM) on a computer. Such an approach is cheaper than the experimental one, which is not even possible in this case.

Ship hull assembly methods

Shipbuilding methods have evolved, starting from the functional and the functional-spatial method, followed by the spatial-zonal and the integrated method (IHOP), and finally the integrated shipbuilding process.

According to Sladoljev (1995) ship hull assembly methods at the building site are the following:

- hull section assembly method,
- hull block assembly method,
- hull module assembly method.

The hull section assembly method is used when assembling a hull on a sloping building site, and its basic element is a section. The maximum section mass in the observed shipyard is up to 200 t. An advantage of this method is the fact that sections can be assembled indoors, where transport is performed by cranes. A disadvantage of this method is the longer hull assembly time due to a large number of sections and section couplings.

The block constituting a part of the hull structure weighing up to 600 t is the basic element of the hull block assembly method. This method is used for hull assembly on a flat or sloping building site. Block transport is mainly performed by the gantry and overhead traveling cranes. An advantage of this method is the fact that block assembly can be organized indoors, as is the case with the ship hull section assembly method. The hull assembly time at the building site is shorter than in the previous method. This method increases the possibilities of fitting out the structure in the pre-assembly phase compared to the hull section assembly method.

The module is a large part of the structure including the final product in its full width, height, and limited length. The hull module assembly method is used on flat building sites. The current trend is to assemble the largest modules possible, and their size is limited by transport possibilities and the specificities of the final product's structure. Transport is performed by ground means of transport with a load capacity of up to 4,000 t. Advantages of using this method are shorter hull assembly time and the possibility to increase fitting out options during module assembly. This method is not carried out in local shipyards due to technological limitations.

Ship hull assembly methods analysis

This paper compares the ship hull section and ship hull block assembly methods using the example of the selected ship. The geometric characteristics of an average section are the following: dimensions: 10.8 × 17.6 × 2.7 m; mass: 99.4 t. The number of hours of work required for the assembly of 67 sections on the building site by this method is 55,200.

When the ship hull is built using the block assembly method, the number of blocks required for the selected ship is 23. The geometric characteristics of an average section are the following: dimensions: 21.9 × 7.6 × 6.8 m; mass: 272.2 t. In addition, 44,500 hours of work are required for all blocks to be assembled.

The duration of the hull assembly sub-process will be reduced because the number of building units in the assembly process is lower by 44, and the total number of hours of work required for assembly is lower by 10,700, which constitutes a 19.4% decrease and is a significant saving.

In order to achieve the advantages of changing the ship hull building method, it is necessary to define the conditions for safe vertical transport of hull structure blocks to the building site. The transport of structures with large dimensions and mass must be safe for all employees, and there must be no structural strains during transport. Lugs and temporary stiffeners are installed on the blocks for vertical transport, as well as to ensure the rigidity of the structure.

It is essential to make a structural analysis of the selected block; the analysis of its results was used to calculate strain and stress values to be applied to create optimal technological instructions for vertical transport (Nurul Misbah, Hardy Sujiatanti, Setyawan, Chandra Ariesta, & Rahmadianto, 2018).

Finite element method

The numerical finite element method is indispensable in structural analysis. It is based on physical discretization, where the continuum with infinite degrees of freedom is replaced by a discrete model of interconnected elements with a finite number of degrees of freedom. It should be noted that the solutions obtained are approximate. Real values can be approached only with the correct definition of the calculation model and correctly selected finite elements, boundary conditions, and loads able to describe the real physical process. For this to happen, it is necessary to understand the physical behavior of the structure being analyzed, as well as to know the theoretical basis of finite elements, and thus the limitations of their use. In addition, it is important to critically analyze the results obtained. Otherwise, the solutions obtained using the available software packages could be wrong, which could, for instance, lead to an incorrect assessment of stress and strain in the analysis of structures and jeopardize the structure's strength and stability (Sorić, 2004).

Solving engineering problems often comes down to solving a system of algebraic equations with a large number of unknown quantities at discrete points. Computers are particularly suitable to solve this (Zienkiewicz, 2005).

The FEMAP (Finite Element Modeling and Postprocessing) software was used for strain analysis (Siemens, 2010). It is advanced engineering software for modeling finite elements of complex engineering products and systems, as well as for presenting the results of their calculations. The FEMAP software makes it possible to model components, assemblies, or entire systems and study their behavior in a given work environment (Senjanović, 1998).

Using FEMAP's options, it is possible to:

- anticipate and improve the product's operational behavior and reliability,
- reduce the need for lengthy and costly testing of physical prototypes,
- test and compare different models and materials,
- optimize the structure and reduce the quantity of necessary material.

Results

This article specifies the general characteristics of shipbuilding sites and transport. The change of the hull assembly method is analyzed on the presented ship. Three different scenarios of structural analysis of vertical transport are created on the example of the selected block. After the calculations were made, the results were compared, and recommendations for defining optimal technological instructions on vertical transport were given.

Shipbuilding site and transport

The hull assembly sub-process takes place at a building site of a shipyard. The building site and facilities for launching ships are capital facilities of each shipyard that significantly affect the following (Mavrić, 1999):

- the layout of other workshops and facilities on the master plan of the shipyard,
- total shipyard production capacity,
- technology and organization of the production process,
- technical level and throughput of other parts of the process,
- costs of building a shipyard.

Building sites are classified according to their purpose, the position of the surface in relation to the waterline, position in relation to the coastline, and the method of ship launching (Mavrić, 1999).

Classification of building sites according to their purpose:

- sites for building and launching ships (longitudinal and transverse slipway, dry dock),
- sites for building and overhaul (horizontal building site, dry dock). Special hydro-technical facilities (floating dock, swiveling sliding ways, slip, vertical ship lift) are used to launch ships in that case.

Classification of building sites according to the position of the surface in relation to the waterline:

- sloping, along the straight line (longitudinal and transverse slipway),
- sloping, on a curve (longitudinal slipway),
- horizontal (dry dock; shipyard area).

Classification of building sites according to the position in relation to the coastline:

- longitudinal (perpendicular to the coastline – longitudinal slipway),
- transverse (parallel to the coastline – transverse slipway).

Classification according to the method of ship launching:

- flooding (dry dock),
- using a floating dock, syncrolift, vertical ship lift, slip, swiveling sliding ways or a

pontoon (horizontal building site in the shipyard area),

- classic launching (longitudinal and transverse slipway).

The general characteristics of the longitudinal slipway shown in **Figure 1** are:

- reinforced-concrete structure build,
- technologically unfavorable for building due to the slope,
- technologically complex, uncontrolled, and relatively risky way of launching ships,
- 170,000 DWT is the maximum permitted size of the ship being built,
- larger ships can be built in two parts,
- relatively low building costs (compared to the dry dock),
- such as they can only be used for building.

Figure 1. A ship on the longitudinal slipway (source: Brodosplit d.d., reproduced with permission).

Shipbuilding transport is defined as an auxiliary system involving the overall movement of materials, tools, energy, information, people, semi-finished products, and products within the shipyard to enable the performance of the core activity of the shipyard or the shipbuilding production process (Mavrić, 1999).

Having regard to the discontinuity of the shipbuilding production process, it follows that the main purpose of a shipyard's transport system is to deliver raw materials from the intermediate warehouses, ensure their movement during technological operations, and ship products or semi-finished products to the intermediate warehouse. In addition to the transport of raw materials, the transport system includes supporting activities such as the collection, receiving, loading, unloading, and reloading of materials, as well as the turning of materials or semi-finished products performed by the means of transport and auxiliaries. Manual handling of the materials occurs very rarely, with attempts to maximize mechanization being made instead. The transport of materials is therefore the most common activity that is continuously performed throughout the production process. The share of transport operations in the entire production cycle amounts to more than 50%, which is also connected to significant costs (Zaplatić, 2009). It should be noted that transport activities do not increase the value of processed material. It is, therefore, necessary to rationally design and exploit the transport system to enable the performance of all tasks at a minimal cost.

According to Mavrić (1999) shipbuilding transport zones are:

- External: representing the shipyard's connection with the suppliers of material and equipment,
- Internal: transport between individual phases of the production process, workshops, working surfaces, warehouses. It is divided into inter-workshop and workshop transport, and it is performed by various ground means of transport and cranes.

All transport activities in the shipyard come down to four basic operations:

- collection of material,
- transport in the vertical plane,
- transport in the horizontal plane, and
- turning (Zaplatić, 2009).

In modern shipyards, said transport operations are performed by cranes, conveyors, and industrial trucks. According to the classification, material-receiving means are used to carry out the first transport operation, encountered during all other transport activities. Conveyors within the shipyard are used solely for horizontal transport. Cranes and industrial trucks have the greatest flexibility and are characterized by the ability to perform simultaneous horizontal and vertical transport, with the former being dominated by the vertical and the latter by the horizontal type of transport activities. The advantage of cranes compared to industrial trucks is the ability to easily rotate, turn and invert the transport units in the air, which is a rather demanding task for industrial trucks, with the exception of rotation in the horizontal plane. Therefore, cranes constitute the most important and indispensable means of transport in the modern shipbuilding industry.

The classification of cranes can be based on several characteristics, such as the load capacity, speed of movement, load-lifting speed, propulsion system, mobility, movement type, or scope of use. The most frequent classification of cranes is based on their design, so there are overhead traveling, gantry, semi-gantry, and floating cranes (Mavrić, 1999).

The need for safe and reliable vertical transport options in the shipbuilding industry is growing due to strains in hull transport, greater responsibilities of crane operators and maintenance technicians, as well as the need for faster performance of planned tasks.

In order to develop the ship hull assembly process, the shipyard increased the load capacity of the crane at the building site by using the new Manitowoc 18000 crane, produced by

The Manitowoc Company, Inc., Milwaukee, USA (**Figure 2**). The crane was placed along the west side of slipway no. 3 for vertical transport and hull block assembly on the slipway. The crane is mobile and has a bogie, a luffing jib, and a nominal load capacity of up to 750 t. The crane boom belongs to the segment type, and the length of the segments can be either 6.1 m or 12.2 m, so the total length of the boom ranges from 42.7 m to 91.4 m. The crane has an accessory – a 21000 MAX-ER hanging counterweight, whose weight may vary depending on the load it lifts.

Figure 2. Manitowoc 18000 crane (The Manitowoc Company, Inc., Milwaukee, USA) (source: Brodosplit d.d., reproduced with permission).

The selected ship

The selected ship was chosen from the shipyard's production program. It is a polar expedition cruise ship shown in **Figure 3**. The main dimensions of the ship are given in **Table 1** (Brodosplit, 2020).

Figure 3. Polar expedition cruise ship selected in this study (source: Meike Sjoer, reproduced with permission).

Table 1. The main dimensions of the ship selected in this study

Dimension	Marking	Value (m)
Length over all	L_{oa}	107.60
Length between perpendiculars	L_{pp}	94.275
Width:	B	17.60
Height to the main deck	D	7.60
Designed draught	T	5.30

The development of the ship hull assembly sub-process will be achieved by using the hull block assembly method instead of the hull section assembly method.

Structure and geometric characteristics of the selected block

The selected block is located in the ship engine room area. The three-dimensional block was modeled in the AVEVA Marine software package (AVEVA Group plc, 2020.) and is shown in **Figure 4**. The dimensions of the block are (L × B × H): 21.9 m × 17.8 m × 6.8 m, and the total mass with installed equipment amounts to about 278 t.

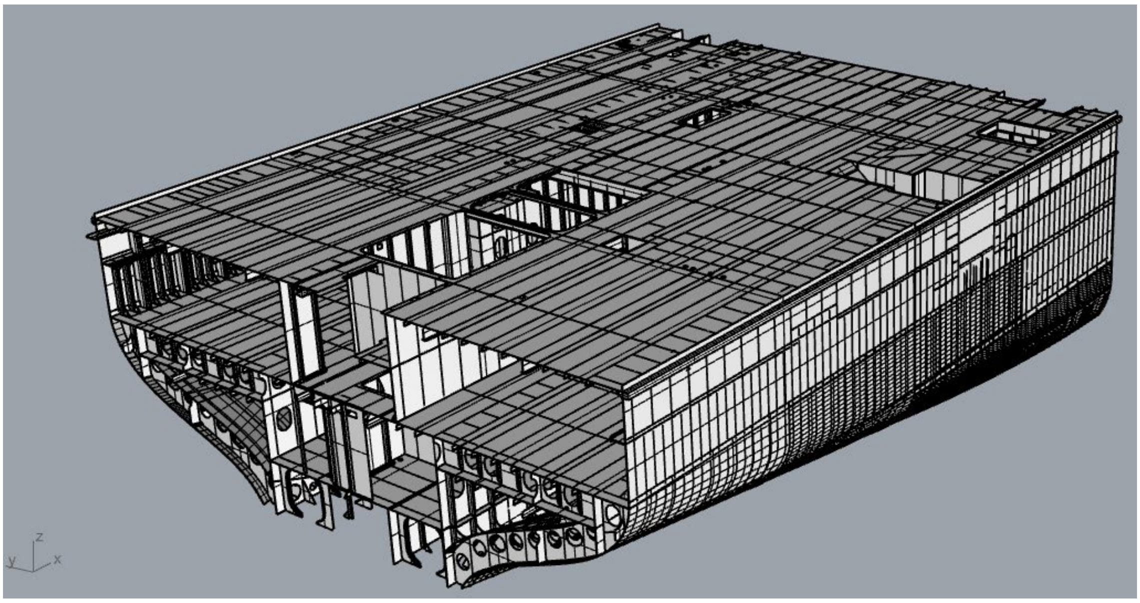

Figure 4. Three-dimensional model of the selected ship's block structure used in this study.

Finite element mesh of the selected block

The selected block encloses the engine room space. It consists of structural elements, namely plates and profiles, so the model is made of flat (plate) and linear (beam) elements. Flat elements are most frequently defined by three (triangle) or four (quad) knots with the corresponding thickness, while linear elements are defined by two knots and the corresponding cross-section. The block equipment is not modeled, but the assumed equipment mass is added to the model instead. The block model consists of 137317 elements in total. **Figure 5** shows the completed finite element mesh of the block defined in the FEMAP software package (Siemens, 2020).

Numerical simulations of the structural analysis of the selected hull block

The modeling of the selected block structure is followed by numerical simulations of various transport circumstances expected in the production process. It is necessary to mount transport lugs on the structure for safe vertical transport given the mass of the selected block. The exposure of block structure to loads is the highest in the transport lug area, so it needs to be additionally strengthened and stiffened with auxiliary structural elements, straps, knees, and stiffeners. According to the SB68005 shipyard standard (Brodosplit, 1993), transport lugs are classified based on their load capacity and marked based on their nominal sizes of 15, 20, 30, 40, and 50. The A50V lug with a load capacity of 500 kN will be used for the selected block (as shown in **Figure 6**).

The dimensions of the lug are defined by the standard. The number and position of the lugs are defined according to the block mass, deck area, and the position of strong longitudinal girders. Eight transport lugs are mounted on the selected block. The lugs are installed 3000 mm to the left and the right of the centerline of the block on frames FR35, FR47, FR53, and FR65. The centerline of the ship (CL) is plane in the middle of ship which divide ship into the left and right side. The frame of the ship (FR) is cross-section of the ship. It can be in various positions lengthwise. For the safety of vertical transport, the ship-

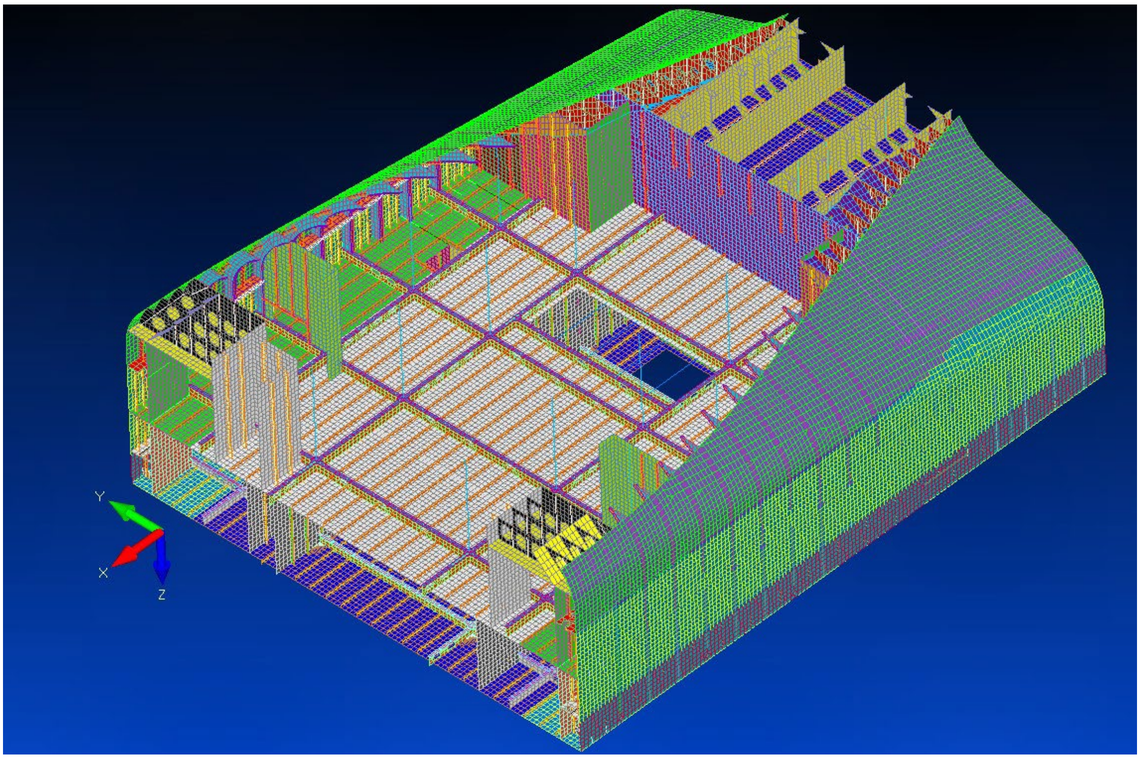

Figure 5. Finite element mesh of the selected ship's block structure used in this study.

Figure 6. A50V transport lug (source: Brodosplit d.d., reproduced with permission).

building standard requires complete welding of all elements in the lug area, as well as all temporary stiffeners with a 1000 mm radius.

For the selected block, three simulations of vertical transport will be made as follows:

- Block transport using 8 transport lugs without temporary structure stiffeners,
- Block transport using 8 transport lugs with the layout of temporary stiffeners according to the shipyard's technological instructions,
- Block transport with 8 transport lugs with the optimized layout of temporary stiffeners.

Structural analysis of the selected transport block without structure stiffeners

The first case involves a structural analysis during transport of the selected block without temporary structure stiffeners. **Figure 7** shows the deformation distribution of the 3rd deck, which is located 7600 mm from the baseline. The thickness of deck plates amounts to 8 mm. The maximum deformation of 27.19 mm is not located in lug area, but on the platform between the 2nd and 3rd deck instead. Deformations are more pronounced on the right side of the block, where the ship's structure has fewer elements that would contribute to additional strength. **Figure 8** shows deformation values on the frames with transport lugs over the entire width of the ship.

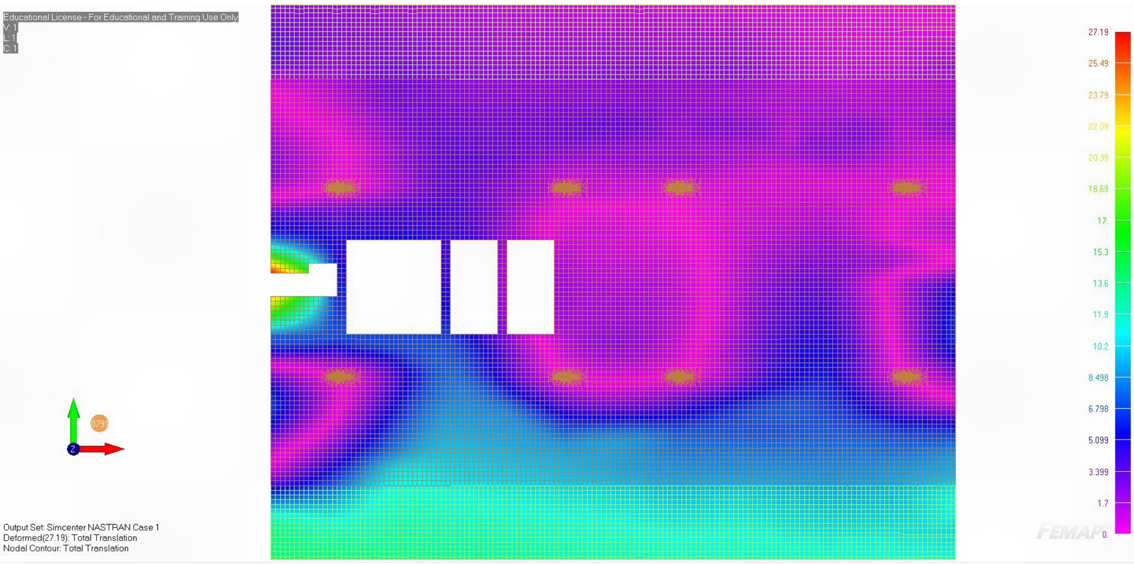

Figure 7. Deformation distribution of the 3rd deck for the selected transport block without structure stiffeners. Deformation scale is defined on the right.

Figure 9 shows the stress distribution of the block structure, and **Table 2** shows stress values on the frames where lugs for transport were installed. The maximum stress on frame FR47 amounts to 1282 MPa, while on other frames it ranges from 400 to 957 MPa.

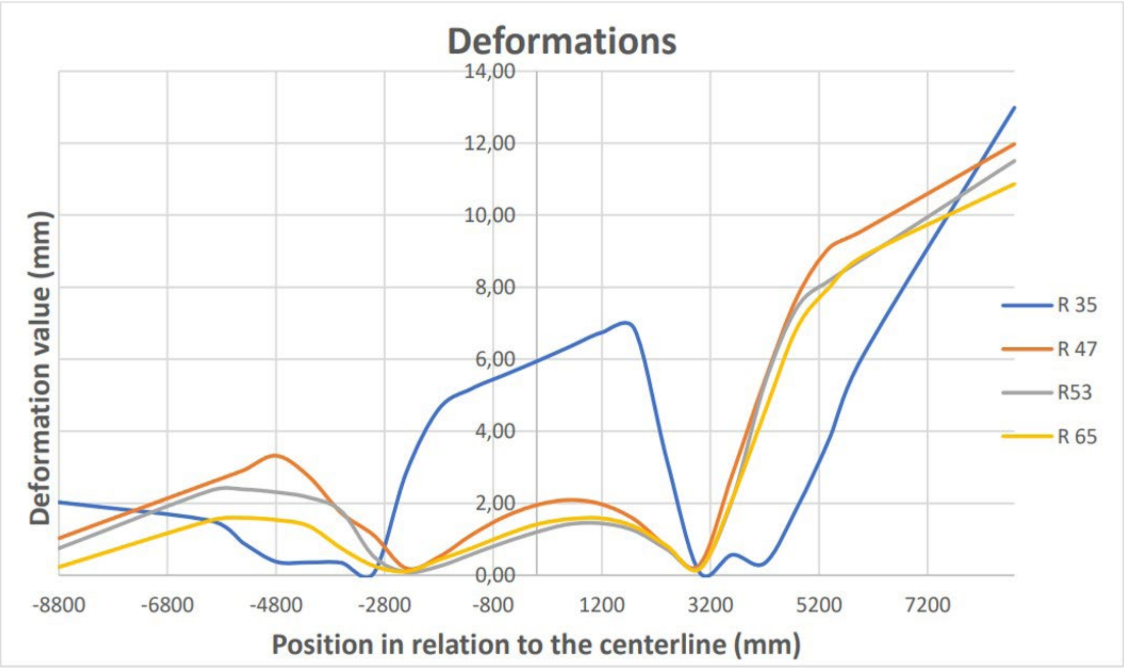

Figure 8. Deformations on the frames of the selected transport block without structure stiffeners. Deformation values are on the frames over the entire width of the ship.

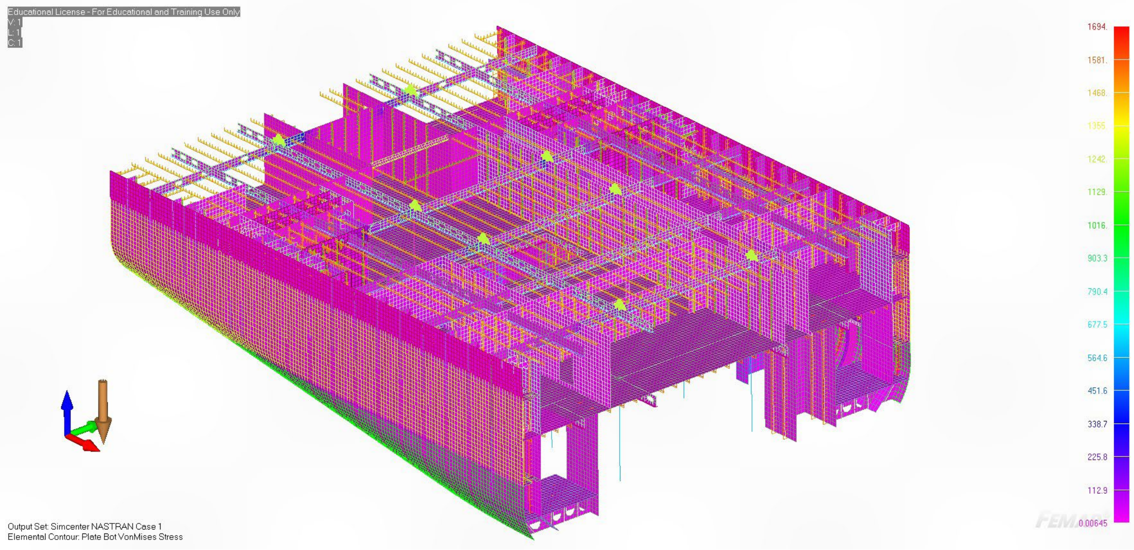

Figure 9. Stress distribution of the selected transport block without structure stiffeners. Stress scale is defined on the right.

Table 2. Stresses on the 3rd deck for the selected transport block without structure stiffeners

Position of the transport lugs on the frame	Stress values (MPa)	
	3000 mm to the left of the centerline (CL)	3000 mm to the right of the centerline (CL)
FR35	399.28	806.99
FR47	1282.93	957.87
FR53	584.43	881.15
FR65	416.22	521.85

Deformation and stress values are several times higher than the permitted 235 MPa, which is the value of the yield strength of the structural material – grade A steel. The conclusion is that such a block cannot be transported without installing temporary structure stiffeners.

Structural analysis of the selected transport block with the layout of temporary stiffeners according to the shipyard's technological instructions

The second case is the structural analysis of block transport with temporary stiffeners defined by the shipyard's technological instructions. Temporary stiffeners are used to temporarily increase the rigidity of the structure being transported. Temporary stiffeners are to be removed following successful transport. Different-shaped steel profiles (I, U, H, T) are used as temporary stiffener material. Their characteristics are high cross-sectional resistance moments thanks to the stiffening of the open and free block ends or strengthening of the area around the transport lugs.

Strengthening of the selected block includes the installation of "U22" stiffeners, plates, and knees between the 2nd and 3rd decks, namely in places where the transport lugs are located. **Figure 10** shows the positions of stiffeners on the selected block for structural analysis.

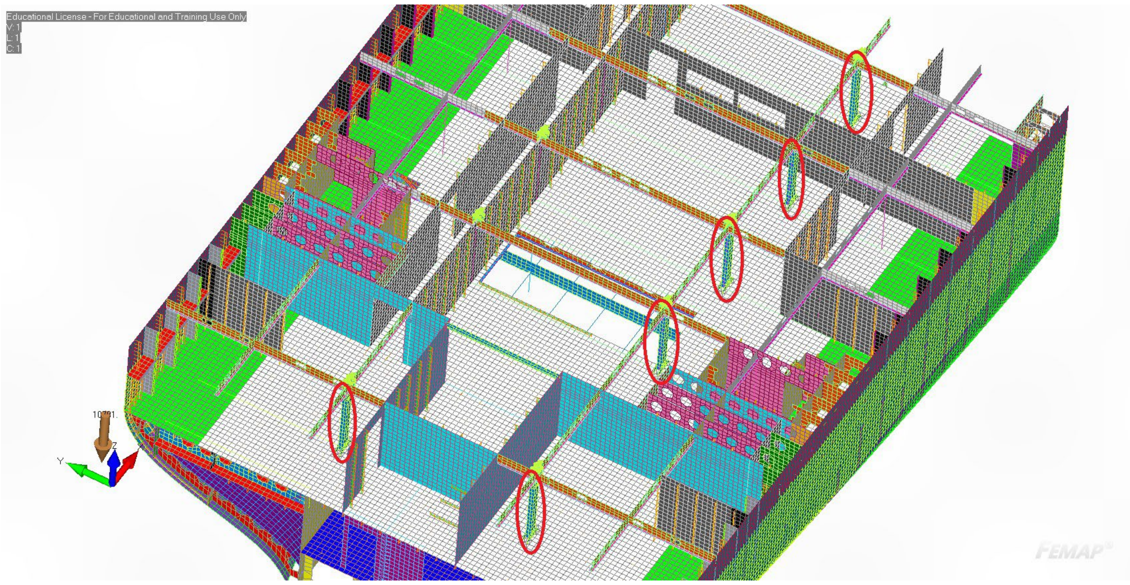

Figure 10. The positions of temporary stiffeners between the 2nd and 3rd deck are in red circles.

Along with the frames connecting the 2nd and 3rd deck, T-profiles are additionally mounted on frames FR47, FR53, and FR59. The length of the T-profile web amounts to 400 mm, and its thickness amounts to 10 mm, while the flange is 150 mm wide and 15 mm thick. These profiles form two webs which increase the rigidity of the structure, and **Figure 11** shows their position in the block model.

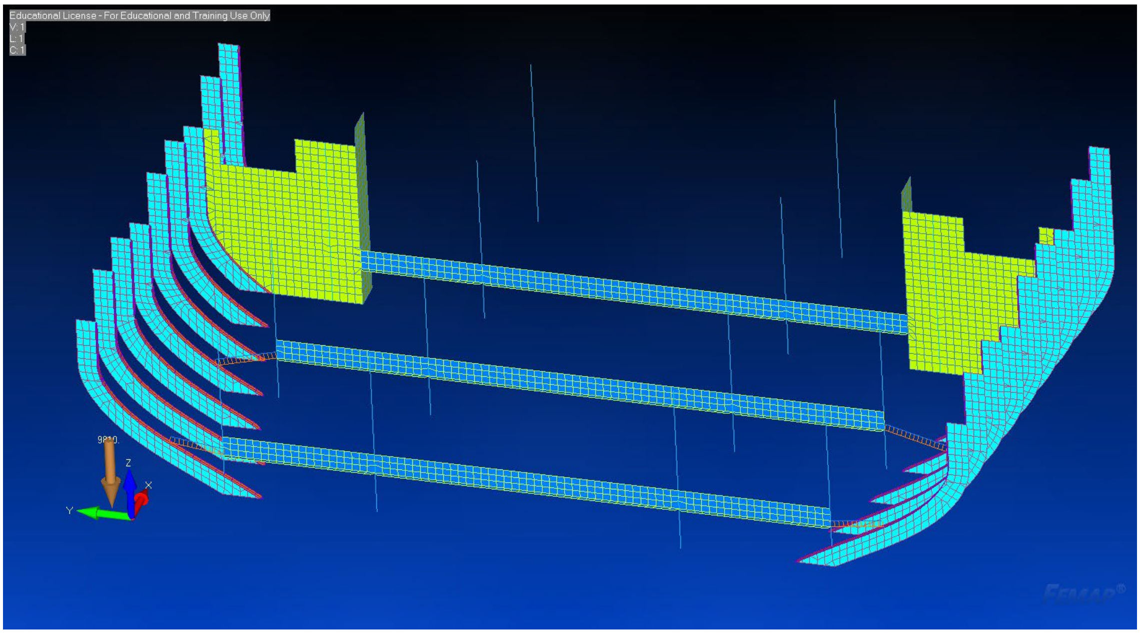

Figure 11. Position of the T profiles temporary stiffeners on frames FR47, FR53, and FR59 which increase the rigidity of the structure.

Figure 12 shows the deformation distribution of the 3rd deck. The maximum deformation of 21.54 mm is located at the free end of the block. Such deformations are easily removed in shipbuilding. Deformations at the free end will be corrected when preparing the section joining, while deformations of the deck plates will be straightened by heating. Deformation values on frames FR35, FR47, FR53, and FR65 are satisfactory. They are shown in **Figure 13**.

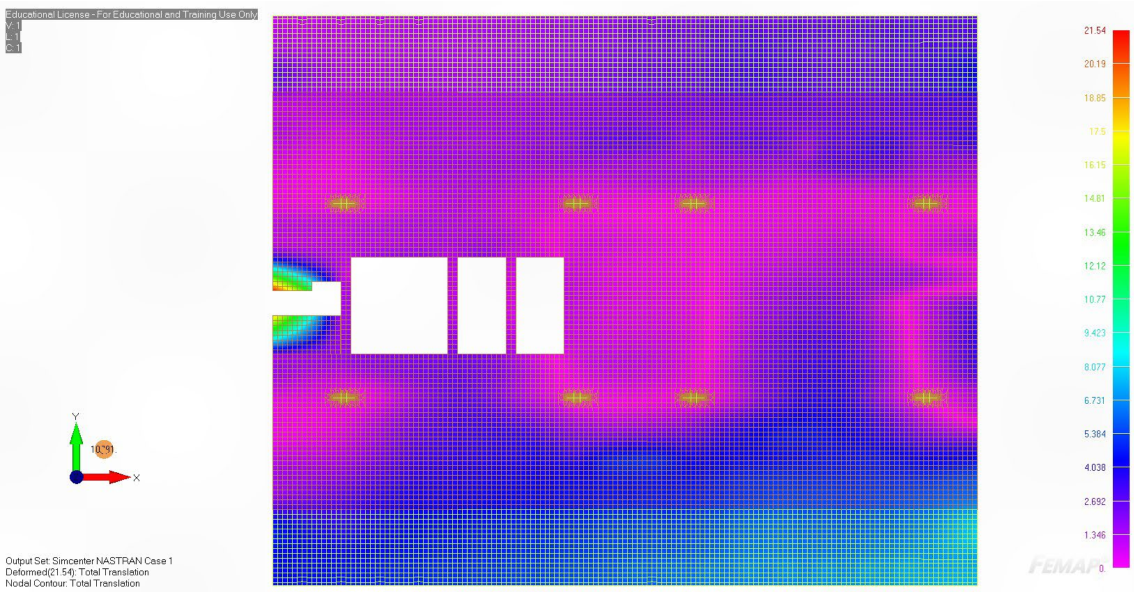

Figure 12. Deformations distribution of the 3rd deck for the selected transport block and the layout of temporary stiffeners according to the shipyard's technological instructions (Brodosplit, 2020). Deformation scale is defined on the right.

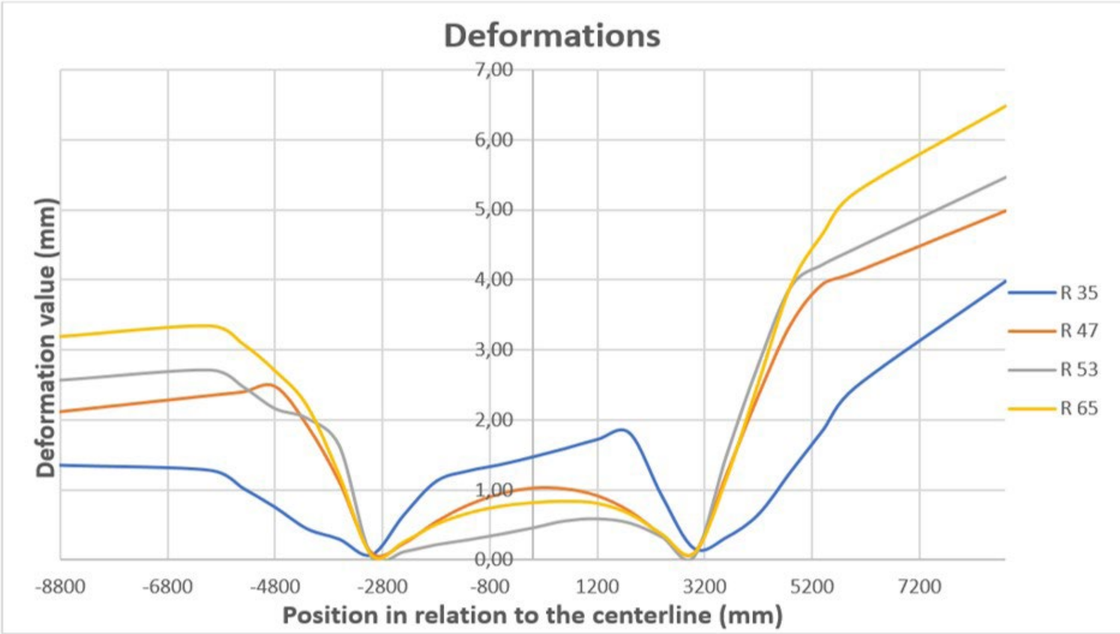

Figure 13. Deformations on the frames of the selected transport block with the layout of temporary stiffeners according to the shipyard's technological instructions. Deformation values are on the frames over the entire width of the ship.

Stress distribution for the selected block is shown in **Figure 14**. Stress values are higher on the block's right side, where there are fewer structure elements. Stress values on frames FR35, FR47, FR53, and FR65 are shown in **Table 3**. Stress values range from 112 to 224 MPa and are lower than the permitted 235 MPa.

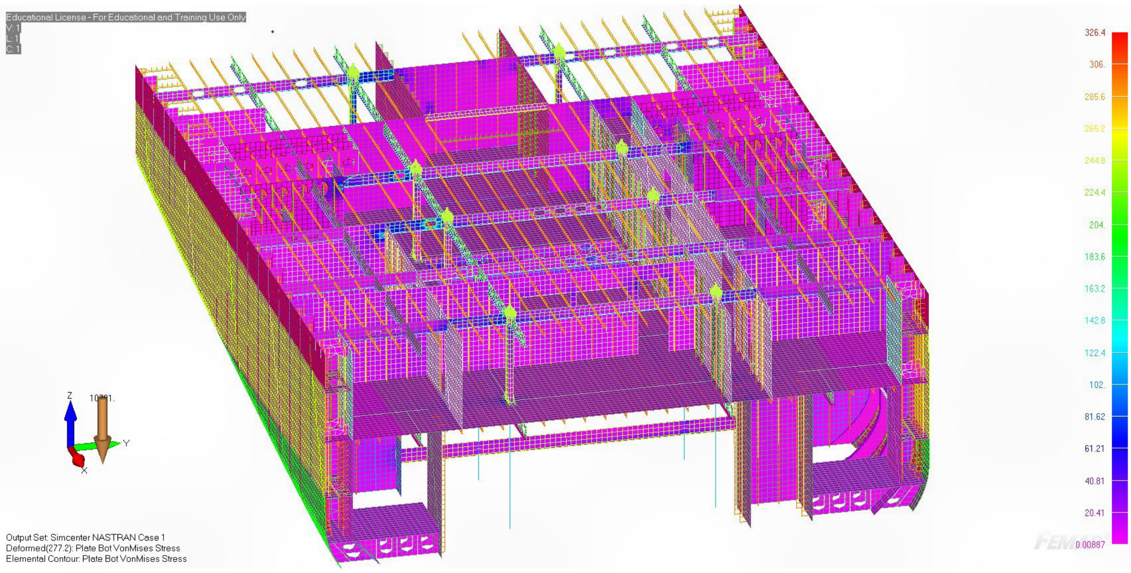

Figure 14. Stress distribution for the selected transport block with the layout of temporary stiffeners according to the shipyard's technological instructions. Stress scale is defined on the right.

Table 3. Stress values on the frames of the selected transport block with the layout of temporary stiffeners according to the shipyard's technological instructions

Position of the transport lugs on the frame	Stress values (MPa)	
	3000 mm to the left of the centerline (CL)	3000 mm to the right of the centerline (CL)
FR35	134.27	207.37
FR47	202.51	224.02
FR53	112.71	139.73
FR65	224.16	192.71

Following a structural analysis, the conclusion is that strain and stress values are lower than permitted. The structure of the selected block has a sufficient number of temporary stiffeners. Thus, safe vertical transport is expected. Stress values at certain positions on the block are lower than 150 MPa, suggesting that some of them are unnecessarily structurally strengthened. It is necessary to optimize the number and characteristics of temporary stiffeners, as they are additional material and lead to additional costs incurred as a result of the hours of work required for element assembly and disassembly.

Structural analysis of the selected transport block with an improved layout of temporary stiffeners.

The improved layout of temporary stiffeners was drawn up based on the results of the previous analysis. Just like in the previous case, strengthening of the selected block includes the installation of "U22" stiffeners, plates, and knees between the 2nd and 3rd decks, namely in places where the transport lugs are located. Strain and stress values at the lower part of the block are less pronounced, and it is evident that T-profiles on the web frames below the second deck are not necessary. An additional reason for this decision is the fact that temporary T-profiles are located in the engine room, where different machines and devices are interfering with the lowering of the block to its position due to their dimensions.

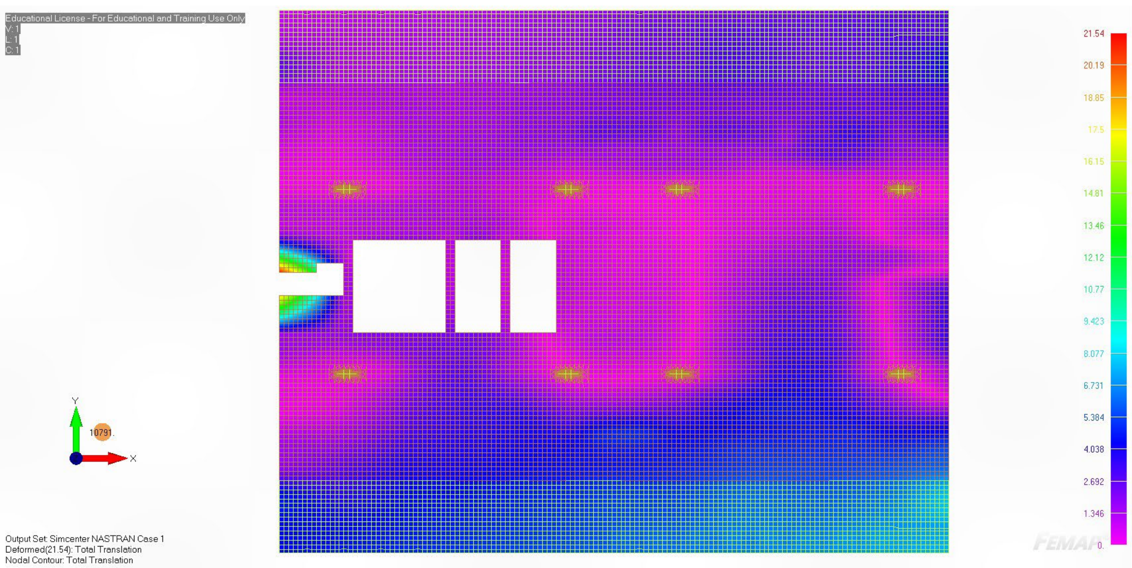

Figure 15. Deformations distribution of the 3rd deck for the selected transport block with an improved layout of temporary stiffeners. Deformation scale is defined on the right.

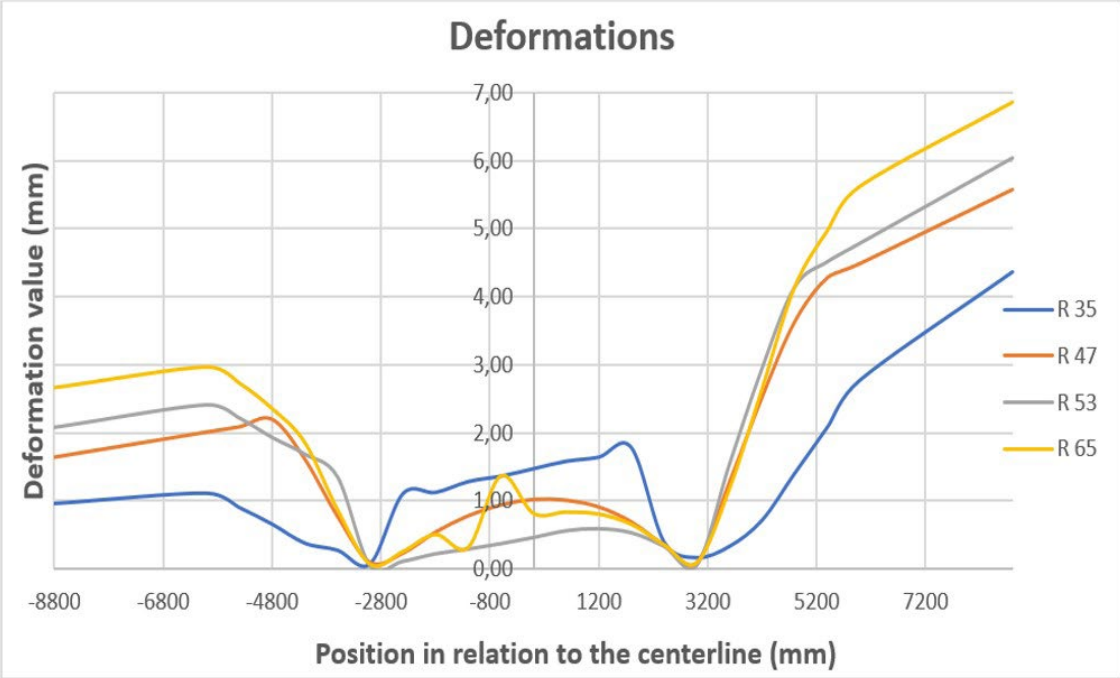

Figure 16. Deformations on the frames of the selected transport block with an improved layout of temporary stiffeners. Deformation values are on the frames over the entire width of the ship.

Figure 15 shows the deformation distribution on deck number 3. Deformation values range from 0.04 to 1.8 mm. Deformation values on frames FR35, FR47, FR53, and FR65 are satisfactory. They are shown in **Figure 16**.

The stress values for the selected block are shown in **Figure 17**. The results of the structural analysis again show that stress values are higher on the block's right side, where there are fewer structure elements. The stress values on frames FR35, FR47, FR53, and FR65 are shown in **Table 4**. Stress values range from 117 to 232 MPa and are lower than the permitted 235 MPa.

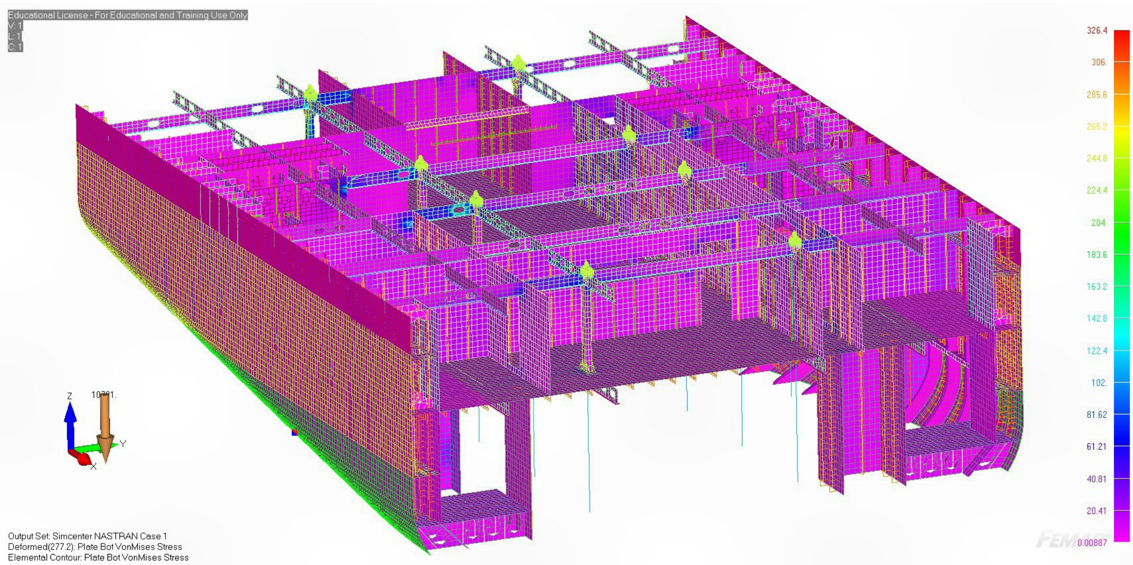

Figure 17. Stress distribution of the selected transport block with an improved layout of temporary stiffeners. Stress scale is defined on the right.

Table 4. Stress values on the frames of the selected transport block with an improved layout of temporary stiffeners

Position of a transport lugs on the frame	Stress values (MPa)	
	3000 mm to the left of the centerline (CL)	3000 mm to the right of the centerline (CL)
FR35	140.79	217.77
FR47	228.75	231.68
FR53	117.96	174.26
FR65	232.34	199.75

Following a structural analysis, the conclusion is that strain and stress values are lower than permitted. The structure of the selected block has a sufficient number of temporary stiffeners. Thus, safe transport is expected. The example shows how the number and layout of temporary stiffeners can be defined using structural analysis, as well as how savings with regard to the quantity of materials and the hours of work required to assemble and disassemble temporary stiffeners can be achieved.

Comparison of results of the structural analysis

Following the structural analyses, the results for all three block lifting simulations will be compared. As for the first case, when the vertical transport of the selected block is analyzed, the calculation shows large, impermissible strains and stresses almost throughout the entire structure. The conclusion is unambiguous – the transport of the selected block cannot be carried out without temporary stiffeners.

In the second case, the transport of the selected block with temporary stiffeners according to the shipyard's technological instructions was analyzed. Strain and stress values are lower than permitted. The structure of the selected block has a sufficient number of temporary stiffeners. Thus, safe vertical transport is expected.

The specification for temporary stiffeners, their mass, and the number of hours of work required for their assembly and disassembly are shown in **Table 5**. According to the shipyard's technological instructions, 56 temporary stiffener elements with a total mass of about 5 t are required. In addition, 147 hours of work are required for their assembly and disassembly.

Table 5. Specification and mass of temporary stiffeners and the number of hours of work required for their assembly and disassembly

Stiffener type	Quantity [pcs]	Mass [kg]	Assembly time [h]	Disassembly time [h]
"C" profile	10	2540.16	23.7	10.8
HP - profile	1	103.53	6.9	1.3
T- profile	13	2041	21.3	19.2
Steel plates	24	286.368	19.9	23.1
Steel plates and brackets	8	101.27	10.8	10
Total	56	5072.32	82.6	64.4

In the third case, a structural analysis of the selected block with an improved number and layout of temporary stiffeners was made. The results of the previous analysis constitute the basis for the new temporary stiffener layout. Neither structure strains nor impermissible stresses were observed in the area below the 2nd deck, so temporary stiffeners were not necessary. In the third case, T-profiles on frames FR47, FR53, and FR59 are not found in the calculation model. An additional advantage of such a decision is the fact that the devices and equipment in the engine room area require a lot of space. Already installed equipment may interfere with the positions of temporary T-profiles on frames FR47, FR53, and FR59.

Following a structural analysis, the conclusion is that strain and stress values are lower than permitted, and the structure of the selected block has a sufficient number of temporary stiffeners. Thus, safe transport is expected. The mass of temporary stiffeners is 2 t lower, which constitutes a 40% saving. The number of required hours of work is also lower. In fact, 40.5 hours of work can be saved on the example of this block. Those hours would otherwise be spent on welding, cutting, and transporting temporary stiffeners, as well as grinding the weld. The hours of work spent on assembling and disassembling temporary stiffeners have been reduced by 27.5%. Savings have also been achieved on additional welding materials. Moreover, electricity consumption and machine use are also lower.

Discussion

This paper confirms the hypothesis that advanced numerical finite element methods and software packages can be used to model complex tasks in shipbuilding on a computer, simulate different scenarios, and analyze calculation results to obtain valuable data for informed decision making (Senjanović, 1998). This working method proved effective, and it could be used not only for all ship hull blocks but also in earlier stages of the shipbuilding production process to increase the level of savings when it comes to the hours of work.

The change of the building method can be achieved by increasing the load capacity of cranes at the building site. In this case, the transport capacity of ship hull structures increases from 170 t to 300 t, which shortens the shipbuilding time at the building site. The main parameters that shorten the duration of the hull assembly sub-process are fewer building units at the building site, fewer structural couplings, and ultimately fewer hours of work (Sladoljev, 1995).

A 60% decrease in the number of building units reduced the number of transport activities to the building site. According to the operational shipbuilding plan, 10,700 hours of work are expected to be saved, which constitutes a 20% saving in relation to the number of hours of work required for the hull section assembly method.

Increasing the dimensions and masses of basic building units leads to the issue with vertical transport, which can be solved by using advanced numerical methods and software packages (Nurul Misbah et al., 2018).

The selected block was modeled using software, and vertical transport simulation calculations were made for 3 cases. The results of the first simulation show that stresses of the block structure exceed the permissible 235 MPa limit several times over, which points to excessive strains. Therefore, such a block is not safe for vertical transport to the building site. The block structure needs to be strengthened with temporary stiffeners.

The second simulation was performed for the ship hull block structure, where temporary stiffeners were installed according to the shipyard's technological instructions. The total number of stiffeners is 56, and their total mass amounts to 5 t, which is equal to approximately 2% of the total block mass. The maximum stress value of structure parts is 224 MPa, while strain values can amount up to a maximum of 2 mm. Strain and stress values are lower than permitted, so safe vertical transport of the block structure is expected. The results of the structural analysis showed that technological instructions can be optimized, thus achieving savings in terms of temporary stiffener material, as well as in terms of the time required for their assembly and disassembly. It was found that all temporary stiffener (T-profiles) below the 2nd deck can be removed, as the strains did not exceed the value of 40 MPa at any location.

The third structural analysis of the block was made on a model without a T-profile, and it represents an improved version of the installation of temporary stiffeners. Strain and stress values are lower than permitted, so safe vertical transport of the block structure is expected. Savings in the amount of 40.2% were achieved in terms of the reduced amount (2 t) of temporary stiffener material. Savings were also achieved in the total number of hours of work required for the assembly and disassembly of temporary stiffeners. Savings amount to 40.5 hours of work, namely 27.5% of the total hours.

Maximum stress values in the second and third simulation are close to the yield limit. We suggest use of general safety factor which can take in account different uncertainties like error in a block mass calculation, numerical errors or errors due to mesh size choice. Also, additional local analyses can be prepared for positions where higher stresses occur. Using the finite element method and modern software packages in solving engineering problems raises the decision-making quality and the level of knowledge, which certainly contributes to increasing the competitiveness of local shipyards in the world market.

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