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IMPROVEMENT OF THE STRUCTURE OF FLOATING DOCKS BASED ON THE STUDY INTO THE STRESSED-DEFORMED STATE OF PONTOON

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Проведено дослідження напружено-деформованого стану залізобетонних плит понтона композитного дока зі зменшеною кількістю набору. Використана уточнена розрахункова схема, при розрахунках згину плит стапель-палуби і днища понтона, яка враховує роботу арматури обох напрямків. Врахування роботи арматури обох напрямків дозволяє точно оцінити міцність конструкції і надати рекомендації щодо проектування конструкцій понтону з точки зору матеріалоємності і оптимального розміру. При моделюванні роботи бетону враховано, що бетон при розтягу має меншу жорсткість на розтяг, ніж на стиск.

Показано, що розроблена конструкція та технологія побудови композитного доку зі зменшеною кількістю набору у понтоні дозволяє розширити технологічні можливості побудови доків. Отримані результати розрахунків зведених напружень в плитах стапель-палуби понтона дока показали, що фактичні коефіцієнти запасу задовольняють вимогам міцності. Враховуючі що конструкція бетонних перекриттів сприймає в декілька разів більший момент спротиву ніж сталь можна збільшити проліт перекриття і рідше розставляти опори-перебірки. Внаслідок цього зменшуються витрати на матеріали та знижуються трудомісткість робіт при побудові доку.

Запропоновано конструкцію та технологію побудови композитного доку зі зменшеною кількістю набору у понтоні. Показано, що встановлення поперечних переборок між внутрішніми бортами через 4 шпації, тобто через 3 метри, а в бетонних баштах відсутність шпангоутів, флорів та бімсів дозволяє зменшити кількість матеріалів, а також знизити трудомісткість побудови доку. Наведені особливості вибору суднобудівного бетону орієнтованого на екстремальні умови роботи морських залізобетонних споруд

Ключові слова: плавучий композитний док, технологія побудови доків, залізобетонні секції, понтон, міцність залізобетонних плит

1. Introduction

Permanent needs of world shipping for ship repairs, inspection, and control over the condition of vessels, maintenance work for the underwater part of vessels, predetermine the elevated demand for floating docks. Construction of docks is a profitable business, constituting one of the important directions to promote domestic products in the world market of shipbuilding. Creating cost-effective and competitive products that meet international requirements for quality necessitates the use of modern composite materials, implementation of advanced technical solutions, as well as innovative construction technology [1].

At almost the same labor intensity of construction, the most metal-consuming, and the worst in terms of operational characteristics, and, consequently, the most expensive is a dock fully made of steel. It has an excess board over water, which leads to an increased amount of ballast that needs to be taken and pumped, the installation of powerful expensive pumps, additional consumption of electricity and prolonged duration of maintenance operations. In addition, the metal dock requires docking for its own repair and technical inspection, which predetermines its regular decommissioning.

The reinforced-concrete dock is completely devoid of all the specified drawbacks; it instead has a number of significant advantages: consumption of a metal is 2–3 times less, the cost of a structure is 30–50 % cheaper, repair-free service life is 2–3 times as long [2]. When the hull elements are made with a greater thickness, the dock becomes rigid, which greatly expands its operational characteristics. The dock can service a vessel that suffered losses in longitudinal strength; in the dock, it is possible to cut into pieces or dispose of a vessel without the danger of its failure due to an impact load. On the contrary, it has a very large weight of the hull that implies the need to apply a higher pontoon and deeper waters or a pit of submersion, as well as large energy cost of refloating. There are certain problems related to air-tightening various functional premises required to accommodate all the necessary machinery and equipment, as well as crew members [3].

The composite docks that have been commonly used at present are made partly from the reinforced-concrete structures, and partly from metallic structures [4]. The pontoon is typically made from reinforced concrete, while the side towers are completely metal-made. This increases the stability of the dock in both surface and submerged condition, as well as reduces the deformations of a stack-deck at the expense of a greater rigidity of the pontoon. Compared to the fully reinforced-concrete dock, a composite dock became lighter, its pontoon became lower, while the lifting force increased at the same dimensions. Thus, the amount of metal used decreases, cheap concrete is applied, operating costs reduce, the dock performance efficiency improves, while its cost is brought down.

Based on the above, we can conclude that a composite structure of the dock is the most rational as it combines the advantages of the steel and the reinforced- concrete hulls. At the same time, it is still a relevant task to define and improve approaches to the selection of dimensions, the optimization of structural parameters and the construction technology for such structures.

2. Literature review and problem statement

As noted in several studies [5, 6], the reinforcement of concrete with fibers leads to a significant increase in the compression strength of concrete (120–170 MPa), which is 3–4 times higher than the indicators for heavy concretes B30-B50 that are common in the Ukrainian shipbuilding. In addition, an increase in strength leads to an increase in the concrete modulus of elasticity, which improves its performance in a combination with steel reinforcement [7, 8]. In order to improve qualitative characteristics of a concrete mixture and to influence the processes of setting and hardening, as admixture is needed. The authors of studies [9, 10] note a positive effect of reinforcing admixtures on water absorption and enhanced stability of the obtained concrete considering the number of freezing cycles. In addition, such concrete is much less susceptible to crack-formation [11]. Another promising direction of concrete manufacture is the application of plasticizers. For example, the authors of [12] performed a comparative analysis of the use of plasticizers based on esters of polycarboxylates by different manufacturers. One of the parameters for comparison was compression strength, which for concretes at the same consumption of cement in the mortar, without admixtures, was 24.5 MPa, and with admixtures 42.9–43.8 MPa, which indicates an almost two-fold strengthening. In addition, such concretes are characterized by the reduced water absorption. Structures made of concrete are exposed to loads that promote deformation. Upon achieving a certain degree of deformation, concrete begins to collapse. In order to protect concrete slabs from possible deformation, it is necessary to use reinforcement in concrete structures.

The prospect of using the new types of concrete, whose mechanical characteristics are significantly higher in comparison with that still applied at enterprises in the shipbuilding industry, predetermines the formation of excessive strength of such structures. Paper [13] reported computations of the stressed state of a concrete slab with steel reinforcement, which revealed certain underload in both the reinforcement and in much of the concrete. The authors substantiated reducing the diameter of reinforcement for the manufacture of slabs for submerged pontoons for a floating dock with a capacity of 25,000 t at a constant thickness of the base. For the docks of a smaller size, excess strength must be even higher at the expense of the protective layer in the reinforcement coating.

Thus, for the case when the mechanical characteristics improve while a modified admixture is applied, it is possible to both reduce the thickness of a concrete base and decrease the number of reinforcement elements. The expected positive effect, in addition to the overall saving of a material, is due to the reduced weight of a structure, improved carrying capacity, the possibility to minimize depth of the submerged part of the pontoon and to bring down the volume of labor costs.

3. The aim and objectives of the study

The aim of this study is to improve the design of composite floating docks based on investigating the stressed-strained state of a reinforced-concrete pontoon.

To accomplish the aim, the following tasks have been set:

– to investigate the stressed-deformed state of the reinforced-concrete slabs in a pontoon of the composite dock with a reduced number of framing sets in the pontoon;

– to calculate the bending of slabs in the stack-deck and the pontoon bottom applying the refined estimation scheme, which takes into consideration work of the reinforcement in both directions;

– to design a structure of the pontoon in a concrete-reinforced floating dock with a reduced number of framing sets;

– to devise a technological sequence for the construction of a floating dock with a reduced number of framing sets.

4. Improvement of the design and construction technology for a composite dock with a reduced number of framing sets in the pontoon

In the structure of a composite framing sets-free pontoon of the dock, the reinforcement that acts on local strength is installed outside in the direction of the smallest spread, while the reinforcement that acts on the overall strength is installed inside the element. Transverse bulkheads between the inner boards are set in 4 quadrats, that is, in 3 meters, while frames, floors and beams are not erected in concrete towers. The structure of a composite framing sets-free pontoon of the dock is shown in Fig. 1.

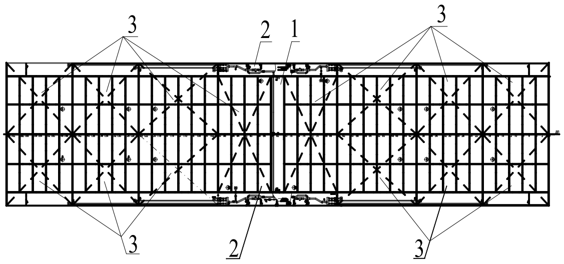


Fig. 1. Structure of the composite framing-free pontoon of a dock: 1 – tunnel 2 – dry compartments, 3 – ballast compartment [14]

Material of the pontoon is reinforced concrete. The class of concrete is B-50, from sulfate-resistant portland cement. Hot-rolled reinforcement with diameters 10, 12, 14, 16, 18, 20, and 22 mm, class AI and AIII, are used to reinforce the elements of the pontoon.

Towers of the dock, including the outer board of the pontoon and the pontoon's bottom under the towers, are fabricated according to a longitudinal system, the pontoon between the inner boards – according to transversal system. Such a solution makes it possible to fabricate the entire reinforced-concrete hull of the pontoon with flat sections.

It is not allowed to apply the reinforcement steel that was exposed to strengthening or profiling by cold processing, as well as thermal strengthening. Manufacture of reinforcing grids is performed at an automatic welding machine or welding in a checkerboard pattern in the environment of CO_2.

Before installing the reinforcing grids on benches in order to assemble the volume, benches are cleaned from concrete and dirt. Benches for forming the concrete sections provide the manufacture of sections with smooth surfaces of uniform thickness and enable the quick removal of moulded sections.

Prior to installing the sections of a stack-deck, the equipment is loaded and the pipelines of a ballast system are assembled. Before assembling, the hull equipment is installed at regular places in the volumetric sections, as well as the foundations, reinforcements under equipment, and the tests are conducted to check water-tightness of intra-section joints and welds.

Before installing the reinforcement, the fitting of a joint is cleaned from dirt, oils, paints, rust that falls away at impact. After cleaning the joints and installing all building constructions, the installation of a wooden-metallic frame is carried out, which must meet the following requirements:

– to ensure the correctness of shapes and dimensions of the concrete-based joint;

– to demonstrate sufficient strength and rigidity;

– to prevent leakage of cement slurry at the compaction of a concrete mixture;

– to provide for an access to deal with minor damages.

In all cases, the concrete in the intra-section joints must exhibit the strength, water resistance, and frost resistance, not less than those required from the concrete for the connecting elements of the pontoon. Elimination of defects of concreting implies the complete removal of all flimsy concrete to be followed by filling the area of a defect with concrete of the same quality as that used for concreting the intra-section joints. Defects in the form of cracks or small holes are preliminary treated at edges by the magnitude that would suffice to fill the cracks with concrete for all depth. The reinforced concrete hull of the pontoon is tested for water resistance after eliminating the defects detected during external observation and upon completion of the installation of inner and welded components.

When setting a ship to the dock, keel blocks are installed at the longitudinal bulkhead of the dock, the loads from which are transmitted to rarely arranged transverse bulkheads of the dock, which ensures the overall transverse strength.

The structure of concrete slabs perceives a several times larger moment of resistance than steel, which makes it possible to increase the spread of a slab and to arrange the supports-bulkheads at a larger distance. The result is the reduced costs of materials, and the decreased labor-intensity of operations when constructing a dock.

5. Calculation of strength of the composite framing-free pontoon of the dock

Study into strength of the reinforced concrete slabs in a pontoon is a complex task. First, it is necessary to consider a joint work of different materials – concrete and steel. Second, concrete is a material with different properties of deformation at stretching and compaction, and at bending its different parts are simultaneously at the compressed and stretched zones. Third, dimensions of the reinforcement are rather small compared to the size of a slab array, thereby complicating simulation using the method of finite elements; it requires a fine grid, and, as a result, incurs large computational cost. In order to study strength of the reinforced-concrete slabs in a pontoon under uniform pressure, we employed the software package SolidWorks Simulation, designed to calculate structurally homogeneous bodies. The package enables running a volumetric analysis of the stressed-deformed state; it is integrated with the SolidWorks three-dimensional simulation system, which makes it possible to efficiently use a graphical interface when simulating the examined objects.

The software package SolidWorks Simulation performs an estimation analysis based on the method of finite elements. This method is a universal tool to investigate complex engineering structures under different conditions of their loading. A geometrical model of the body is conventionally split into a certain number of small parts of simple shape, which are called the finite elements that interact at common points – nodes. The behavior of each node in a finite element is described by the assigned number of parameters, determining which makes it possible to estimate the stressed-deformed state of both the elements and the examined structure in general.

The computational package employs one of the varieties of the method of finite elements – the method of displacements. The basic unknowns, predetermined in the first place, is the displacement of nodes at which the finite elements interact with each other. At these same nodes, such fictitious efforts that correspond to the displacements are applied that characterize the action of stresses along the borders that join the adjacent elements.

Because the accepted basic unknowns are the nodal displacements, it is possible to determine them following the construction of a rigidity matrix for a discrete model of the structure [13]. This matrix is formed from the matrices of rigidity of individual finite elements and it establishes the relationship between the nodal displacements of a discrete model and the external load to the original structure. In fact, it is the result of building the equations of equilibrium at nodal points that represent a system of linear inhomogeneous equations of algebra with unknown nodal displacements.

For the three-dimensional problems, the package employs a tetrahedral finite element with ten nodal points (Fig. 2).

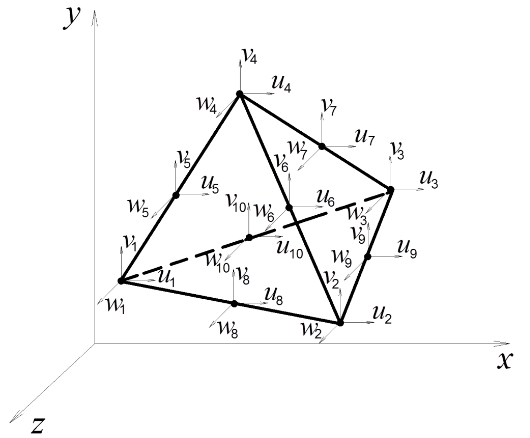


Fig. 2. Nodal displacements in a tetrahedral finite element

After determining the displacement of nodes, one can calculate deformations and stresses for the entire model. The represented (equivalent) stresses are computed based on the Mises energy theory.

In order to reduce the total number of the elements employed, given the dual symmetry of slabs, the calculation of the stressed state was performed for the 1/4 part of the slab, denoted by shading in Fig. 3. In this case, the models show the reinforcement for two mutually perpendicular directions, as well as concrete, which works separately on compression and separately on strength. It is important that a feature in the work of concrete is the reduced resistance during work at stretching at the expense of lower mechanical characteristics and due to the formation of micro-and macro-cracks, which is why the compressed and stretched concrete were simulated via individual geometrical bodies with different indicators for strength and rigidity. Modulus of elasticity of the reinforcement was taken to equal $2.0 \cdot 10^{11}$ Pa, for concrete at compression – $0.38 \cdot 10^{11}$ Pa, for concrete at stretching – $0.11 \cdot 10^{11}$ Pa.

Cross-section of the reinforced concrete slabs for a stack-deck of thickness 140 mm and maximum size in plan 6,700×3,000 with the reinforcement of diameter from 12 to 20 mm is shown in Fig. 4, *a*. Schematic of the reinforcement of bottom slabs with a thickness of 160 mm in the region of exposure to the maximum hydrostatic pressure is shown in Fig. 4, *b*.

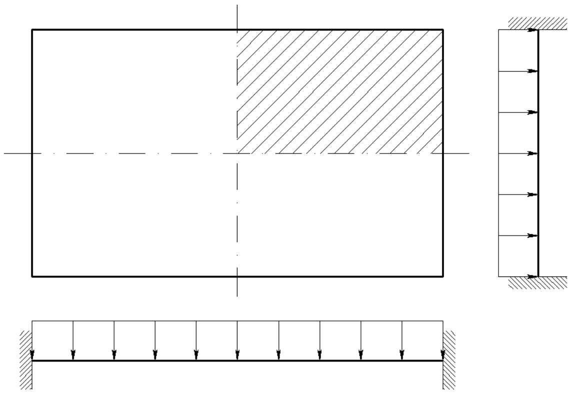


Fig. 3. Estimation scheme of the dock's pontoon slabs

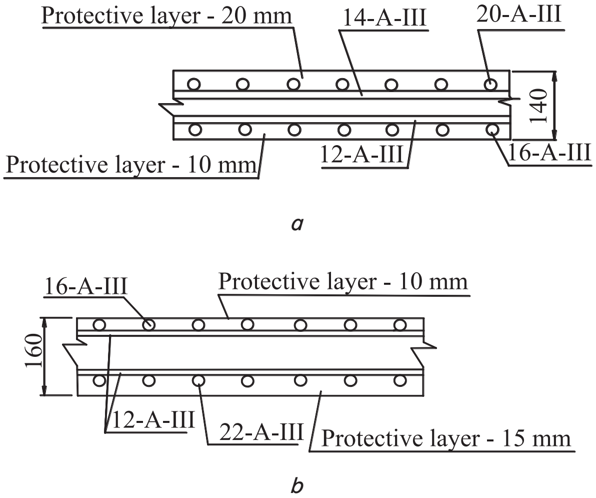


Fig. 4. Schematic of reinforcement of the reinforced-concrete slabs: *a* — stack-deck; *b* — bottom

Fig. 5 shows a fragment of splitting the reinforced-concrete slab of a dock's pontoon into finite elements. The estimated structure of the reinforced concrete slab of the deck is divided into 5,001,360 finite elements of tetrahedral shape with 6,765,687 nodal points for a quarter of the slab, the bottom into 3,915,831 elements with 5,310,498 nodes. In order to reduce the number of elements, we applied when splitting the models an adaptive finite-element grid with the increased size of the elements at the surfaces of slabs, and denser to the cylindrical surfaces of reinforcing elements whose simulation requires a rather fine grid, given their small relative size.

The slabs of the stack-deck were calculated for the uniform lateral hydrostatic load at full submersion, which is 60 kPa at the level of the stack-deck with a dry compartment. The bottom slabs were calculated for the uniform lateral hydrostatic load at full submersion, which is 92 kPa at the level of main plane with a dry compartment. Calculations showed that the maxima of the cumulative stresses based on the Mises criterion (energy theory) occur in the reinforcement, located at the opposite side from the application of load, compressed in the middle of long sides. The stresses amount to 120 MPa for the bottom slabs (Fig. 6, *b*) and 102 MPa for the deck slabs (Fig. 6, *a*), with a reserve factor of 3.25 and 3.82, respectively, which exceeding the required coefficient by 2.3 and 2.7 times. In this case, the rated stresses in a concrete base is 7–10 times below the maximum stresses of reinforcement in the respective direction (Fig. 7, 8).

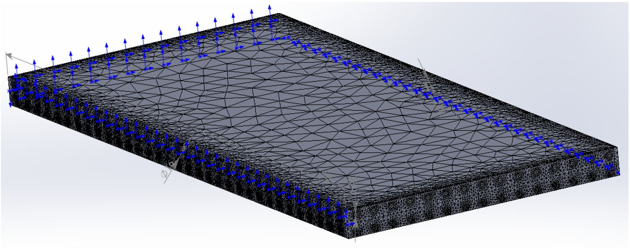


Fig. 5. A fragment of splitting the reinforced-concrete slab of the pontoon's stack-deck into finite elements

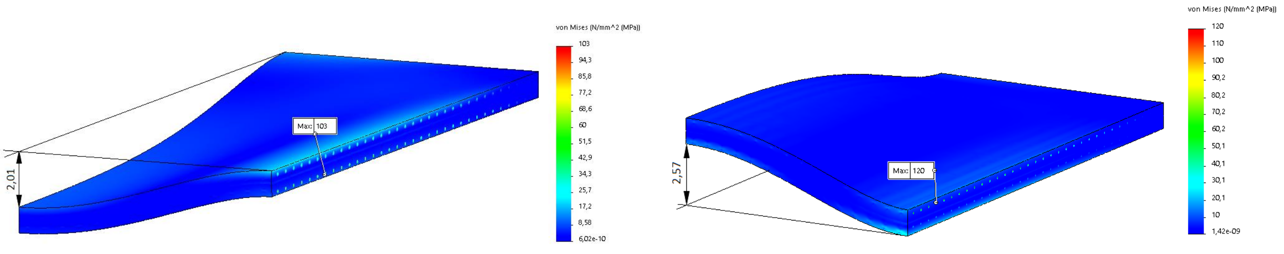
The most stressed was the reinforcement that is the farthest from the surface loaded with pressure, as well as the one that is located along the short edges of the slab, which agrees with the theory of bending continuous rigid slabs.

Thus, given the level of the calculated normal and cumulative stresses at a reduced number of framing sets, the strength of slabs in the stack-deck and the bottom is sufficient.

6. Discussion of results of studying the stressed-deformed state of the reinforced-concrete pontoon

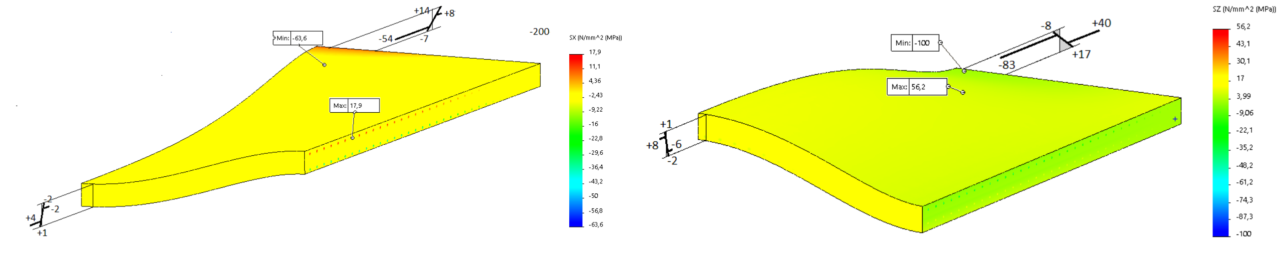
The finite-element model was calculated for the cases of complete submersion of the dock in a quiet water, without taking into consideration possible dynamic loads. This is related to the conditions for operation of the pontoon in the water areas of ports and plants where such a load is almost absent. The model would need refinement for other conditions and cases of loading.

The proposed finite-element model accounted for work of the reinforcement in both directions – longitudinal and transverse, rigidly clamped beams on the pontoon bulkheads. Structural elements in the joint between a pontoon and elements of the side towers were not taken into consideration. A distinctive feature of the model is the interpretation of the compressed and stretched part of the concrete with two separate bodies, which makes it possible to take into consideration, in addition to the difference in the limits of strength at compression and stretching, the difference in the elastic characteristics of the model related to a decrease in rigidity along the direction of stretched elements at the expense of the formation of micro- and macrocracks.



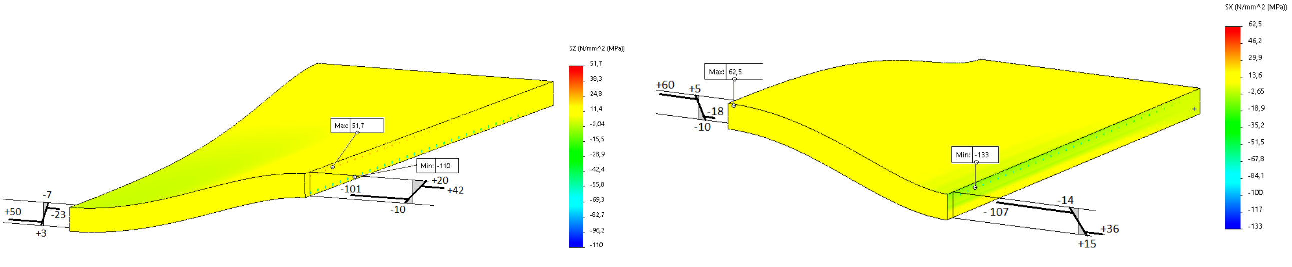
a *b*

Fig. 6. Cumulative stresses and deflection arrows in slabs: *a* – stack-deck; *b* – bottom



a *b*

Fig. 7. Normal stresses along the long sides: *a* – stack-deck; *b* – bottom



a *b*

Fig. 8. Normal stresses along the short sides: *a* – stack-deck; *b* – bottom

Construction of the grid of finite elements for a given model as a solid body has caused certain difficulties related to small diameter of the reinforcement, which in turn requires the small size of the elements along the boundary of transition concrete-steel and, as a consequence, a large number of them. That significantly increases the duration of preparation and carrying out the calculations.

The derived magnitudes of cumulative stresses in the slabs of a stack-deck in the dock's pontoon with a lifting force of 5,000 t showed that the actual reserve ratios at a reduced number of framing sets satisfy the requirements for strength. At a maximum load, the cumulative stresses, by Mises, in the reinforcement do not exceed 120 MPa at a maximum of normal stresses of ~100 MPa in the transverse direction, which corresponds to the reserve ratio of 3.82 for the reinforcement used in decked slabs. In the longitudinal direction, the reinforcement is also underloaded, especially in a compressed region. Ratio of yield limit for the steel reinforcement of class A-III to the maximal cumulative stresses in the bottom slabs is not less than 3.25.

Such reserves, even in the case of applying the heavy concrete of class B-50 ensure the strength of a stack-deck and a bottom with the excess reserve. This can be explained by using an excessive amount of concrete related to maintaining the minimum thickness of a protective coating by concrete of the reinforcement and the effective distance between reinforcement in the layer. This enables further optimization in terms of material consumption by reducing the thickness of concrete slabs and the diameter of the reinforcement used.

The model is optimized for the minimal quantity of reinforcements in order to reduce metal consumption. However, the parameters that affect the strength of such structures most are the thickness of slabs in the reinforced concrete pontoons. The optimization of slab thickness, and, as a result, the amount of concrete used, is a promising area for further research.

7. Conclusions

1. Our research into the stressed-deformed state of reinforced-concrete slabs in the pontoon of a composite dock with a reduced number of framing sets in the pontoon has showed that the strength of slabs in a stack-deck and in a bottom is sufficient. At maximum load, a strength reserve coefficient is 3.82 for the deck slabs, and 3.25 to the bottom slabs.

2. When calculating the bends of slabs in a stack-deck and in a pontoon's bottom, we employed the refined estimation scheme, which takes into consideration work of the reinforcement along both directions, which made it possible to precisely estimate the level of stresses and to provide recommendations on the design of structures in terms of material consumption and optimal size.

3. The designed structure of the composite pontoon of a dock is more effective in terms of material consumption. Installing the transverse bulkheads between internal boards in 4 quadrats, that is, in 3 meters, as well as the absence of frames, floors and beams, in concrete towers, makes it possible to reduce the amount of materials used and, consequently, the total weight of the dock.

4. We give the principal technological sequence for the construction of a reinforced-concrete pontoon with a reduced number of framing sets in the docking chamber, which makes it possible to significantly reduce the labor intensity in the construction of a composite dock by reducing the volume of technological operations.

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