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МАТЕРІАЛОЗНАВСТВО

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Use of Fine-Grained Heat-Strengthened Steels to Increase the Operation Qualities of Bunker Capacities from Thin-Walled Galvanized Profiles

Purpose. The work is aimed to study the use efficiency of fine-grained heat-strengthened steels (mainly 10G2FB) for steel bunker capacities. At the same time, the structural scheme of such a structure using corrugated steel sheets is considered as the main variant. **Methodology.** To achieve this purpose, a series of numerical calculations was carried out for a steel bunker capacity of a pyramidal-prismatic type with overall dimensions in plan view of 6×5.2 m and a total height of 4.5 m. The capacity was designed for complicated working conditions, in particular, increased loads, including long-term dynamic ones. The potential possibility of operating the container under conditions of high or low temperatures was also taken into account. At the same time, both the traditional structural scheme of a bunker capacity with horizontal stiffening ribs and the developed structural scheme based on corrugated steel sheets were analyzed. The calculations were carried out by the finite element method based on the SCAD for Windows project complex. **Findings.** Based on the results of the analysis and comparison of the data obtained in numerical calculations, it was found that the use of fine-grained heat-strengthened high-strength steels (for example, steel 10G2FB) for bunker capacities, both the traditional structural scheme with stiffening ribs and the developed structural scheme based on corrugated sheets, allows reducing material consumption by about 30% in both cases. At the same time, due to the good performance of fine-grained heat-strengthened steel 10G2FB, both at high and at low temperatures, it can be effectively used for steel bunker capacities that work in difficult conditions. **Originality.** The possibility and efficiency of the use of fine-grained, heat-strengthened high-strength steels for the construction of a steel bunker capacity is estimated. At the same time, such an estimation was given not only for structures of the traditional structural scheme with horizontal stiffening ribs, but also for bunkers with a developed structural scheme based on corrugated sheets. **Practical value.** From a practical point of view, quantitative parameters of the stress-strain state were obtained during investigations of various design variants for a steel bunker capacity. The data are presented in a compact form that is easy to evaluate and compare. They allow us to state about the improvement of the operation characteristics of capacities and the potential reduction of the risks of their failures and accidents during operation.

Keywords: fine-grained heat-strengthened steel; thin-walled galvanized profile; finite element method; bunker capacity

Introduction

In recent decades, a fairly new and interesting direction in the practice of creating and further operation of building structures for various purposes is the use of thin-walled galvanized profiles. Some features of their production and application in modern conditions of Ukraine are described in the publication of a master's student of Dnipro National University of Railway Transport named after Academician V. Lazaryan (DNURT), whose thesis was devoted to this issue [2].

Thin-walled galvanized profiles are widely used for steel silo capacitive structures designed

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mainly for grain storage. However, various factors often cause failures and accidents of such structures [3]. The situation is further complicated by the small thickness of the profiles themselves (not more than 3 mm), which forces creating packages of several sheets connected by bolts (Fig. 1).

Fig. 1. Packets of sheets from thin-walled galvanized profiles for steel silo capacitive structures

Such silo capacities are often installed at facilities related to transport and storage operations. These include, for example, railway stations or river and seaports.

In addition to silo capacities, bunker tanks are also often located at such facilities. They, like silos, perform the technological functions of accumulation and dosed distribution of bulk material stored in them over time.

Regarding bunker tanks, especially those operating under difficult production conditions and designed for high loads, one of the co-authors of this article, Professor D. O. Bannikov, has developed a special design scheme [10]. It is designed to absorb not only static but also dynamic loads, which are quite significant in bunker-type tanks.

However, to obtain the desired load-bearing ability, it is often necessary to lay in the hopper structure thickness of the load-bearing elements not less than 10 mm. This is especially true in the case of operation of such facilities under adverse and complicated conditions: high loads, low or high temperatures. It is for these conditions that the use of fine-grained heat-strengthened high-strength steels of the 10G2FB type instead of traditional steels of the usual St3 type proved to be quite efficient. It was tested on the example of blast-furnace jacket structures and confirmed its high practical efficiency [4]. The choice of steel type is due to the new technological capabilities of Metinvest Engineering OJSC, which has mastered the production of such steels with improved mechanical properties and an expanded range of sheet thicknesses.

10G2FB steel was used during the design of the steel pyramidal-prismatic bunker of the bypass track of furnace-charge feeding. The customer of the object is Pivnichstal PJSC, so the bunker facilities operate at low temperatures.

The general description of a design of these bunker constructions, the theoretical substantiation of possibility and efficiency of use of steel 10G2FB are presented in the separate publication [15]. The bunkers are made according to the traditional structural scheme with horizontal reinforcing stiffening ribs. The calculated economic effect in the prices of 2019 amounted to about 0.5 million UAH (almost $ 20,000), and the total weight reduction was about 4 tons per bunker with dimensions of 6×5.2 m in plan, with a total height of 4,5 m and a usable volume of 40 m^3.

However, as has been repeatedly noted in the monograph [10], as well as in many other works by Professor D. O. Bannikov, the traditional structural scheme with stiffening ribs has certain reserves of load-bearing ability. It is possible to use them due to the specially developed panel structural scheme based on corrugated sheets of steel.

Purpose

In regard to the above, the purpose of our publication is to study the efficiency of fine-grained heat-strengthened steels (mainly grade 10G2FB) for steel bunker tanks. Thus, structural scheme of such structure with the use of corrugated steel sheets variant was considered as the basic.

Methodology

First of all, it should be noted that the work of corrugated steel sheets is quite complex. The current normative document of Ukraine on the design of steel structures [6] does not pay special attention and does not contain relevant recommendations for the design of such structural elements.

This issue is partially addressed in a recently published monograph [1]. However, the corresponding analytical solutions, even for the simplest cases, have a whole system of empirical correction factors.

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Thus, in the domestic research practice there are actually no full-fledged theoretical developments that would allow theoretical determining of the load-bearing ability of corrugated steel sheets.

The situation is further complicated by such an aspect as the lack of clear recommendations in the current regulations [5] to determine the loads from the action of bulk material on the structural elements of the bunker capacity.

Since the use of corrugated steel sheets for capacitive structures is the newest direction in construction, the foreign literature is also quite limited in terms of the application of analytical approaches. For example, in the classic monograph [12] there is no information on such topics.

Currently, in foreign practice there are only partial studies of corrugated profiles, primarily closed-type profiles [14]. Another part of the research covers the search for more efficient protective surfaces for thin-walled profiles [13]. Also, some studies raise the issue of mounting and manufacturing of structures of thin-walled profiles [17].

However, even the accumulated European experience in the calculation and design of corrugated profiles, presented in the national standards [7, 8], which are translations of the relevant European standards, is quite limited. These standards provide only general recommendations for determining the stress-strain state for some cases, but there are no full analytical solutions.

Given this situation, as the main research method the finite element method was chosen, which has become extremely popular in recent decades and which is constantly being modernized [20]. Its practical implementation took place on the basis of SCAD for Windows domestic project complex [9]. This choice was made according to the construction orientation of this complex, in contrast to other developments, such as SolidWorks, CosmosWork, Nastran or WinMachine, which have a machine-building orientation [16]. During the research, the experience of school of soil mechanics of DNURT was also used [18, 19].

As already mentioned, steel pyramidal-prismatic bunker was the object of the study. The height of the prismatic part was 0.5 m, and the pyramidal hopper – 4.0 m. The prismatic part also formed a bunker beam, through which the capacity rested on the elements of the bunker trestle. The width of the discharge mouth, as well as its length were taken equal to 1.2 m, the angle of hopper inclination with such geometric dimensions was about 60°.

Slag scrap, whose density, according to the initial data, reaches 3 t/m^3 and the internal friction angle is 45° is provided as one of the loaded bulk materials. The minimum coefficient of dynamics, according to the customer data, was 1.3. In addition, it was necessary to take into account the action of vibrating feeders, whose operation mode is provided around the clock. Technological load from the sole weight of bulk material is set in accordance with the developments presented in the monograph [10].

The constructed finite-element models for research were plate systems (Fig. 2.) The finite element is an isoparametric shell element from the standard library of the SCAD for Windows complex. Fastening of bunker capacities is modeled in such a way to receive the hinged scheme of their operation.

Findings

A separate issue during the research was to determine the characteristics of steels, provided for the design of steel bunker capacity. The tests were conducted by a specialized organization, State Enterprise Ya. Yu. Osada Scientific Research Tube Institute (SE SRTI). Both the chemical composition of steels (Table 1) and their tensile mechanical characteristics for different temperatures were determined separately (Table 2).

The chemical composition was determined by photoelectric spectral analysis on Spectromax X LMM04 atomic emission spectrometer manufactured by SPECTRO in Germany. According to the test protocols, the room temperature was +24 ºC, relative humidity – 40%.

The mechanical characteristics were established during the tensile test of standard cylindrical specimens with a diameter of 10 mm on a test machine type P-5.

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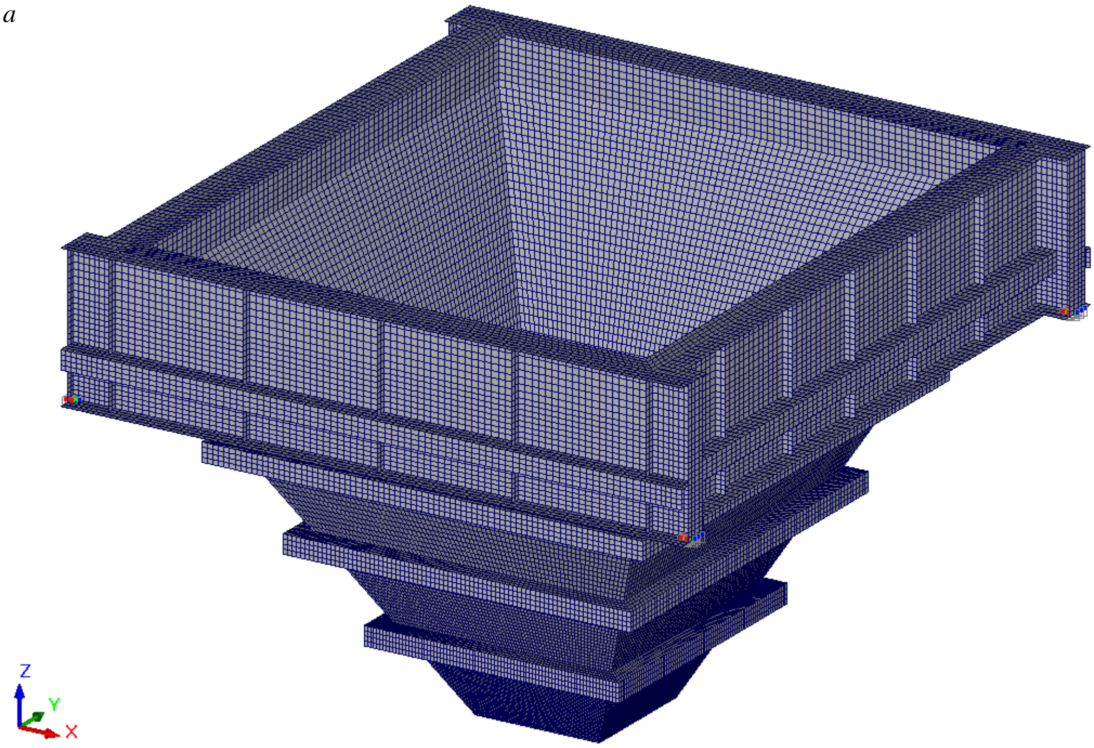
a



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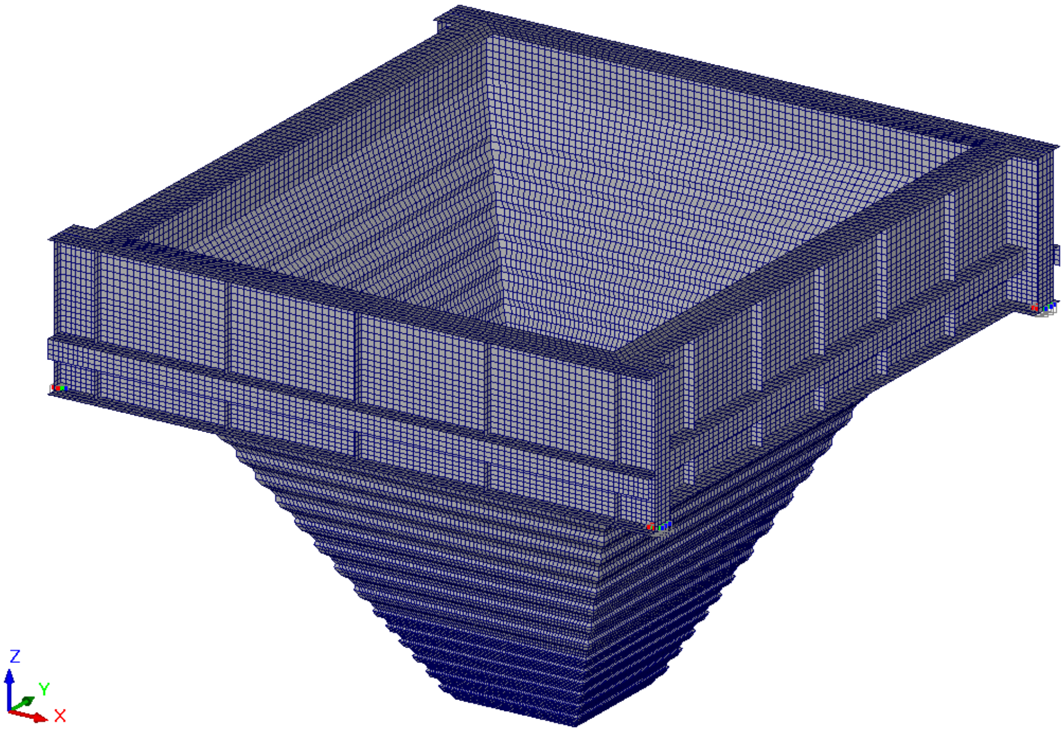

Fig. 2. Finite-element model of steel hopper capacity:
a – traditional structural scheme with horizontal stiffening ribs;
b – developed structural scheme with horizontal corrugated elements

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Thus, based on the obtained test results in terms of operation of the bunker capacity under difficult conditions of high loads, as well as high and low temperatures, 10G2FB steel grade was the best. It has a mixed structure of fine ferrite and dispersed carbide and of the second phase carbonitride, which is achieved by microalloying and controlled rolling with the addition of chromium, niobium, vanadium and titanium. These admixtures have a grinding effect on the original austenitic grain [11]. It also provides 10G2FB steel with good impact resistance at KCV^{-15} = 59 J/cm^2 and KCU^{-60} = 39 J/cm^2. Therefore, steel grade 10G2FB was taken as the main for the design of steel bunker capacity.

As a result of the numerical calculations, quantitative results were obtained (Table 3), and the general pictures of the deformed state are shown in Fig. 3 (for ease of perception, half of the model is presented).

As can be seen from the results obtained, for the bunker capacity designed with horizontal corrugated elements, the deformed state is more uniform. Accordingly, the stress state is also more uniform, with fewer stress concentrators, which is very important for difficult operating conditions (especially for low temperatures). Weight indicators remain almost the same.

Table 1

Chemical composition of tested steels

Steel grade	Mass fraction of elements, %					
	Carbon (C)	Manganese (Mn)	Silicon (Si)	Sulfur (S)	Phosphorus (P)	Chromium (Cr)
St3sp	0.16	0.50	0.20	0.004	0.009	0.04
09G2S	0.09	1.64	0.55	0.004	0.009	0.03
10G2FB	0.09	1.64	0.55	0.004	0.009	0.03
Steel grade	Mass fraction of elements, %					
	Nickel (Ni)	Copper (Cu)	Vanadium (V)	Aluminum (Al)	Niobium (Nb)	Titanium (Ti)
St3sp	0.03	0.01	–	0.04	–	–
09G2S	0.05	0.03	0.001	–	–	–
10G2FB	0.05	0.03	0.001	0.033	0.05	0.02

Table 2

Mechanical properties of tested steels

Steel grade	Test temperature, °C	Yield strength, MPa		Strength limit $\sigma_в$, MPa	Relative elongation, δ_5, %	Contraction ratio, ψ, %
		$\sigma_{0,2}$	$\sigma_Т$			
St3sp	+20	–	278	418	36	67
	+600	108	–	155	60	87
	+800	37	–	55	83	76
09G2C	+20	–	343	492	36	74
	+600	167	–	227	40	85
	+800	63	–	48	91	77
10G2FB	+20	–	462	584	27	65
	+600	258	–	285	27	83
	+800	73	–	84	59	86

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Table 3

Quantitative results of numerical analysis

Indicator	Constructive scheme with horizontal			
	stiffening ribs		corrugated elements	
	St3sp steel	10G2FB steel	St3sp steel	10G2FB steel
Stability coefficient	13.41	5.14	15.27	6.43
Wall deflection, mm	7.27	14.24	5.15	7.35
Weight, kg	15 456	11 216	15 532	11 310

It should also be noted that the presence of a corrugated surface on the inside of the bunker capacity creates additional opportunities for special self-lining due to the retention of bulk material. In the practice of design, this method of lining the inner surface is created artificially, attaching special horizontal retaining elements, which in turn increases the complexity of manufacturing the structure.

Originality and practical value

This publication evaluates the possibility and efficiency of using fine-grained high-strength steels for the construction of steel bunker capacities. And the similar estimation is given not only for constructions of the traditional structural scheme with horizontal stiffening ribs, but also for bunkers with the developed structural scheme on the basis of corrugated sheets.

From the practical point of view in the course of the conducted researches of various structural variants of steel bunker capacity, quantitative indicators of a stress-strain state are received. The data is presented in a compact and easy to evaluate and compare form. They suggest an improvement in the performance of bunkers and a potential reduction in the risk of their failure and accidents during operation.

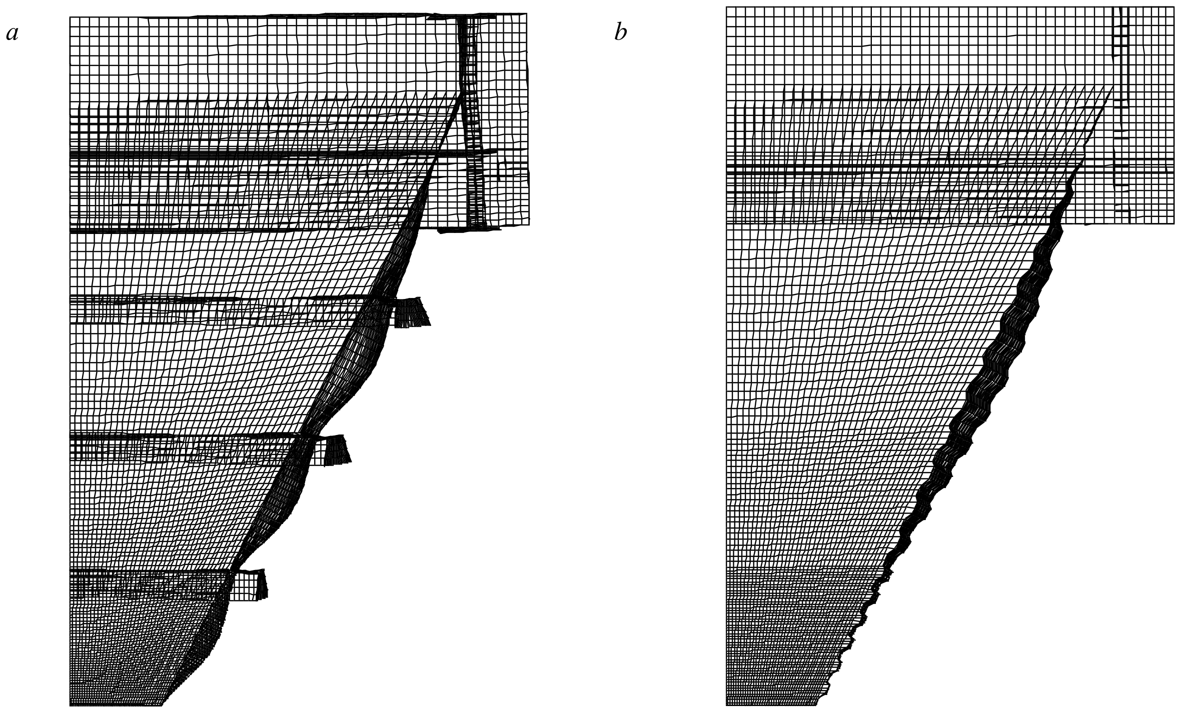

Fig. 3. Deformed state of steel bunker capacity made of 10G2FB steel:
a – traditional structural scheme with horizontal stiffening ribs;
b – developed structural scheme with horizontal corrugated elements

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Conclusions

Based on the assessment of the stress-strain state of the steel bunker capacity, made of steels of different grades, it should be stated the following:

1. The use of fine-grained heat-resistant steels of high strength (for example, 10G2FB steel grade) for bunker capacities of both traditional structural scheme with stiffening ribs, and developed structural scheme based on corrugated sheets can reduce the material consumption of the structure by about 30% in both cases.

2. Due to good performance at both high and low temperatures, fine-grained heat-resistant steel grade 10G2FB can be effectively used for steel bunkers operating under difficult conditions. Such conditions include working conditions in the northern regions or with hot bulk materials.

3. It should be noted the possibility of improving the performance of steel bunker capacities, in particular durability and reliability, due to the improved mechanical properties of the steel type used. In operation, this potentially reduces the possible costs of repairing and maintaining bunker capacities.

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Застосування дрібнозернистих термозміцнених сталей для підвищення експлуатаційних якостей бункерних ємностей із тонкостінних оцинкованих профілів

Мета. У роботі передбачено дослідити ефективність застосування дрібнозернистих термозміцнених сталей (переважно марки 10Г2ФБ) для сталевих бункерних ємностей. При цьому як основний варіант розглянуто конструктивну схему такої споруди з використанням сталевих гофрованих листів. **Методика.** Для досягнення поставленої мети проведено серію чисельних розрахунків сталевої бункерної ємності пірамідально-призматичного типу з габаритними розмірами в плані 6×5,2 м й загальною висотою 4,5 м. Ємність спроектовано для ускладнених умов роботи, зокрема підвищених навантажень, у тому числі й тривалих динамічних. Також до уваги взято потенційну можливість експлуатації ємності за умов підвищених або понижених температур. При цьому проаналізовано як традиційну конструктивну схему бункерної ємності з горизонтальними ребрами жорсткості, так і розроблену конструктивну схему на основі сталевих гофрованих листів. Обчислення проведено методом скінченних елементів на базі проектного комплексу SCAD for Windows. **Результати.** На підставі аналізу та зіставлення отриманих під час чисельних розрахунків даних установлено, що застосування дрібнозернистих термозміцнених сталей високої міцності (на прикладі сталі марки 10Г2ФБ) для бункерних ємностей як традиційної конструктивної схеми з ребрами жорсткості, так і розробленої конструктивної схеми на основі гофрованих листів дозволяє знизити матеріалоємність споруди приблизно на 30 % в обох випадках. При цьому завдяки хорошим показникам роботи як за підвищених, так і за понижених температур дрібнозерниста термозміцнена сталь марки 10Г2ФБ може бути ефективно застосована для сталевих бункерних ємностей, які працюють в ускладнених умовах. **Наукова новизна.** Оцінено можливість та ефективність застосування дрібнозернистих термозміцнених сталей високої міцності для конструкції сталевої бункерної ємності. Причому подібну оцінку надано не тільки для споруд традиційної конструктивної схеми з горизонтальними ребрами жорсткості, а й для бункерів із розробленою конструктивною схемою на основі гофрованих листів. **Практична значимість.** Із практичної

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точки зору в ході проведених досліджень різноманітних конструктивних варіантів сталевої бункерної ємності отримано кількісні показники напружено-деформованого стану. Дані представлено в компактній та зручній для оцінки й зіставлення формі. Вони дозволяють стверджувати про поліпшення експлуатаційних характеристик ємностей і потенційне зниження ризиків їх відмов та аварій під час експлуатації.

Ключові слова: дрібнозерниста термозміцнена сталь; тонкостінний оцинкований профіль; метод скінченних елементів; бункерна ємність

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