EFFECTIVENESS EVALUATION OF STEEL STRENGTH IMPROVEMENT FOR PYRAMIDAL-PRISMATIC BUNKERS

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Abstract

In accordance with the recommendations of specialized professional literature, steel pyramidal-prismatic bunkers are projected for a service life of 20 years. However, in practice this term is often twice, or even three times lower. This is especially true for complicated operating conditions, in particular the effect of increased loads and low temperatures. Existing design techniques for such structures, both in European practice and the design practice of Ukraine and other CIS countries do not pay attention to these aspects. Therefore, in the practice of operation, the increased accident rate of steel bunker capacities has already become virtually a common occurrence.

One of the possible ways to solve this problem is presented, which consists of using instead of traditional steels of ordinary strength with high plastic properties, steels of increased or high strength with reduced plastic properties. At the same time, clear theoretical recommendations are provided for choosing the right steel depending on the operating conditions, primarily when exposed to increased loads. The recommendations are presented in a form convenient for practical engineering applications.

The proposed approach allows to reduce the material consumption of structures of this type on average according to theoretical estimates by 25–30 % without reducing their bearing capacity. Their durability is also further enhanced by improving performance at low temperatures. Thus, the applied aspect of such a solution to this above problem is the possibility of increasing the overall reliability of steel bunker capacities, as well as reducing the cost of their periodic maintenance and repair work.

A practical illustration of the presented approach is also given on the example of the design of bunkers of a bypass track for supplying charge materials for blast furnaces of one of the metallurgical plants of the northern location. As a result, this created the preconditions for monetary savings of about 0.5 million UAH in prices 2019 (about 20,000 USD).

Keywords: capacitive structure, steel pyramidal-prismatic bunker, 10G2FB steel, thin-walled structure.

1. Introduction

Steel pyramidal-prismatic bunkers are an integral functional link in the factories of the full cycle of the metallurgical industry. Such bunkers are located at the junction of various technological operations associated with bulk materials (ores, agglomerates, concentrates of charge departments of sinter plants, scrap, matte, slag, crushed stone, coal, etc.). Such structures are intended for temporary storage of these materials before the next technological operation.

Despite such a variety of materials, the pyramidal-prismatic appearance of bunker structures turned out to be the most successful for their storage.

In the most difficult and adverse conditions, there are receiving bunkers in which bulk materials are fed to enterprises. At the same time, unloading is carried out by significant volumes from automobile or railway transport. This creates a number of static and dynamic effects on bunker structures, forms an aggressive external environment with dust and residues of materials mixed with air. Therefore, the design and operation of bunkers for bulk materials is an extremely complex and responsible field that requires the use of qualified approaches and high-quality materials.

Now Ukraine has gained considerable experience in the creation and operation of bunker capacities at numerous enterprises of the metallurgical industry in different countries [1, 2]. However, despite this, the service life of such steel bunker structures rarely exceeds 30-40 years, and the period of trouble-free operation is 5–7 years [3]. Meanwhile, replacing and even carrying out repair work on steel bunkers under the conditions of the existing production is quite difficult, but sometimes just about impossible. This is due to the peculiarities of the technological processes of the metallurgical industry, which for the most part consist of round-the-clock continuous cycles. Needless to say, the failure of at least one technological unit, such as, for example, bunker capacities, can lead to a significant drop in production volumes. Also, in this case, specialized metallurgical equipment, designed for continuous operation at elevated temperatures, is likely to fail.

Related to this is the relevance of research in the design of steel bunker capacities for the metallurgical industry, which aims to theoretically and practically increase the durability of these structures. The aim of research is effectiveness evaluation of increasing the strength of steels for the construction of a steel pyramidal-prismatic bunker in difficult operating conditions.

To achieve the stated aim, the following objectives are set:

– to assess the possibility of steel strength improvement in the design of a steel pyramidal-prismatic bunker for the conditions of increased loads according to the calculation method of Ukraine;

– to evaluate the possibility of increasing the strength of steels in the design of the steel pyramidal-prismatic bunker for the conditions of increased loads according to the European calculation method;

– to carry out practical testing of the proposed approach on the example of the design of the bunkers of one of the metallurgical plants of the northern location.

2. Materials and research methods to effectiveness evaluation of the steel strength improvement

To assess the possibility of steel strength improvement in the construction of a steel pyramidal-prismatic bunker, let's consider the operation of its sheet sheathing as the most material-intensive structural element.

According to the modern design approach of Ukraine [4], the strength of sheet sheathing with a thickness t (cm) is described by the expression (1):

$$\frac{N}{t \cdot R_y} + \frac{6 \cdot M_{max}}{t^2 \cdot R_y} \le 1, \tag{1}$$

where R_y – the calculated steel resistance (kgf/cm²); N – the longitudinal force in the sheathing (kgf/cm), which is determined by the expression (2):

$$N = \sqrt[3]{\frac{E \cdot t \cdot P^2 \cdot d^2}{24 \cdot (1 - \mu^2)}}, \tag{2}$$

where E – the steel elasticity modulus (kgf/cm²); P – the pressure load of bulk material on the sheathing (kgf/cm²); d – the length of the smaller side of the sheathing section of the bunker between the edges (cm); μ – Poisson's ratio of steel (b/s); M_{max} – the maximum bending moment in the sheathing (kgf), which is determined by the expression (3):

$$M_{max} = \frac{P \cdot d^2}{8} - S \cdot f, \tag{3}$$

where S – the thrust force in the sheathing (kgf/cm), which is determined by the expression (4):

$$S = \frac{\pi^2 \cdot E \cdot t^3}{12 \cdot (1 - \mu^2) \cdot d^2}, \tag{4}$$

f – the deflection of the sheathing section of the bunker between the stiffeners (cm), which is determined by the expression (5):

$$f = \frac{4 \cdot P \cdot d^2}{\pi^3 \cdot (N + S)}. \tag{5}$$

The rigidity of sheet sheathing according to the classical design approach should correspond to the expression (6):

$$f \le \frac{d}{50}. \tag{6}$$

To determine the limit value of the load on the sheathing of the bunker capacity, which simultaneously ensures the strength and rigidity of the sheathing, it is necessary to solve a system of two equations (1) and (6). Since these equations are nonlinear, their solution can be obtained in numerical form.

According to the modern European design approach [5], the strength of sheet sheathing with a thickness of t (cm) is described by the expression (7):

$$\frac{6 \cdot M_{max}}{t^2 \cdot R_y} \le 1, \tag{7}$$

where the maximum bending moment M_{max} (kgf) is determined by the expression (8):

$$M_{max} = \alpha \cdot P \cdot d^2; \tag{8}$$

α – a coefficient depending on the ratio of the length of the larger side b (cm) of the sheathing sections of the bunker between the stiffeners to the length of the smaller side d (cm) (**Table 1**).

Table 1
Coefficient α values

b/d	α
1	0,048
1,2	0,063
1,4	0,075
1,6	0,086
1,8	0,095
2	0,108
3	0,119
4	0,123
>5,0	0,125

Substituting expression (8) into expression (7), equating the left and right parts, after mathematical transformations, let's obtain expression (9) to determine the maximum thickness of the bunker sheathing (cm):

$$t = d \cdot \sqrt{\frac{6 \cdot \alpha \cdot P}{R_y}}. \tag{9}$$

The deflection of the sheet sheathing (cm) according to the classical design approach is described by the expression (10):

$$f_{max} = \frac{(48 \cdot \alpha - 1) \cdot P \cdot d^4}{32 \cdot E \cdot t^3} \leq \frac{d}{50}. \tag{10}$$

After mathematical transformations, equating the left and right parts, let's obtain the expression (11) to determine the maximum thickness of the bunker sheathing (cm):

$$t = d \cdot \sqrt[3]{\frac{(48 \cdot \alpha - 1) \cdot 50}{32 \cdot E}}. \tag{11}$$

Equating expressions (9) and (11) after mathematical transformations, let's obtain expression (12) to determine the threshold value of the load on the bunker sheathing (kgf/cm²):

$$P = \left(\sqrt{\frac{R_y}{6 \cdot \alpha}} \cdot \sqrt[3]{\frac{25 \cdot (48 \cdot \alpha - 1)}{16 \cdot E}} \right)^6. \tag{12}$$

Thus, for load values less than those calculated by expression (12), the sheathing thickness will be determined by the stiffness condition, and more by the strength condition. Let's also note that in this case, the limiting values of the loads do not depend on the size of the section of the sheet sheathing d, but are determined solely by the calculated characteristics of the steel.

3. Research results of effectiveness evaluation of the steel strength improvement

The result of the numerical solution of the system of equations (1) and (6) is presented in **Table 2**. It shows the obtained limit values of the load, as well as the sheathing thickness, which corresponds to it. Since the calculated resistance is often multiplied by an additional coefficient of work γ_c, which is recommended to be equal to 0.8 for bunker structures, data are also provided for low values of the calculated steel resistance.
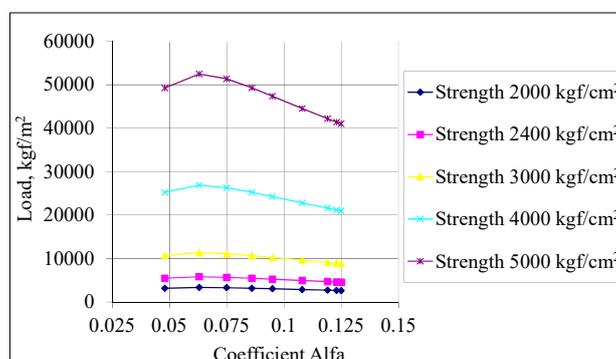
Table 2

Limit values of the load according to the design approach of Ukraine

R_y, kgf/cm²	P, kgf/cm²	t, cm	R_y, kgf/cm²	P, kgf/m²	t, cm
1400	18010	0,50	3600	41250	1,00
1600	19350	0,53	3800	44430	1,06
1800	20810	0,57	4000	47820	1,11
2000	22420	0,61	4200	51410	1,17
2200	24180	0,65	4400	55200	1,23
2400	26090	0,69	4600	59210	1,29
2600	28170	0,74	4800	63420	1,36
2800	30420	0,79	5000	67860	1,42
3000	32850	0,84	5200	72520	1,48
3200	35460	0,89	5400	77400	1,54
3400	38260	0,94	5600	82500	1,61

As shown in the **Table 2** data, the limit values of the load are quite high. At the same time, the sheathing thickness is rather insignificant. Thus, this approach will not contribute to steel strength improvement. However, this approach leads in practice to numerous accidents and failures of steel pyramidal-prismatic bunkers, especially for low temperature conditions [6].

Let's also note that the obtained limit values of the loads and the sheathing thickness do not depend on the size of the section of the sheet casing d, but are determined solely by the calculated characteristics of the steel.

Based on the obtained expression (12), for various values of coefficient α and various values of the calculated resistance of steel R_y, graphs are constructed – **Fig. 1**. From these graphs it is clearly seen that the threshold value is quite insignificantly dependent on the coefficient α. And for practical purposes, it is enough to focus on its average value equal to 0.086. The numerical values obtained for this case are given in **Table 3**. As in the previous case, data in **Table 3** is also given for low values of the design resistance of steel.

Fig. 1. The nature of the change in the values of the limit value of the load

Table 3

European design approach load limits

R_y, kgf/cm²	P, kgf/cm²	t, cm	R_y, kgf/cm²	P, kgf/m²	t, cm
1400	1082	0,66	3600	18395	1,70
1600	1615	0,76	3800	21634	1,80
1800	2299	0,85	4000	25233	1,89
2000	3154	0,95	4200	29210	1,99
2200	4198	1,04	4400	33585	2,08
2400	5450	1,14	4600	38376	2,18
2600	6930	1,23	4800	43602	2,27
2800	8655	1,33	5000	49283	2,37
3000	10645	1,42	5200	55437	2,46
3200	12919	1,52	5400	62082	2,56
3400	15496	1,61	5600	69239	2,65

As shown in the **Table 3** data, the limiting values of the load are an order of magnitude lower than in the previous case. At the same time, steel of low strength, which is traditionally used for steel bunker capacities, provides the necessary load-bearing capacity of the bunker structure at a load level of about 4000–5000 kgf/m². At higher loads, it is advisable to increase the strength of steel, since it is strength that will limit the bearing capacity of the structure. The thickness of the bunker capacity sheathing should also be increased in comparison with the design approach of Ukraine, which will help reduce the accident rate of such structures and increase their durability.

Thus, using this approach, when conducting practical calculations of the effectiveness of increasing steel for pyramidal-prismatic bunkers, it can be estimated quite simply and most importantly, reasonably.

4. Discussion of the results of effectiveness evaluation of the steel strength improvement
To illustrate the practical effectiveness evaluation of the steel strength improvement in the design of a steel pyramidal-prismatic bunkers, the design of a real bunker of a bypass feed track of

charge materials for blast furnaces is carried out. The customer of the facility is Severstal (Canada), so the bunker structures operate at low temperatures.

The total height of the bunkers according to the technological design should be 4.5 m with a floor width of 6 m and a floor length of 6 m, and the width of the discharge opening is taken as its length of 1.2 m. The inclination angle of the funnel with such geometric dimensions is about 60°. A slag scrap is provided as one of the loaded materials, the density of which, in accordance with the initial data, reaches 3 t/m³, and the angle of internal friction is 45°. The minimum required volume of the bunker is 40 m³. The minimum coefficient of dynamism according to the customer is 1.3. In addition, it is necessary to take into account the action of the vibratory feeder, the operation mode of which is supposed to be around the clock.

Based on these data, the vertical load on the casing of the bunker is calculated from the pressure of bulk material in its lower part. Given the adopted on the basis of the recommendations of the project approach of Ukraine, the reliability coefficient for the load is equal to 1.3 and the dynamic coefficient is 1.5, its value is almost 30 t/m². For the conditions of the designed object, the normal pressure on the wall of the funnel of the bunker structure is about 12 t/m². According to the **Table 3** in this case, it is necessary to use high-strength steel with a design resistance of about 4300 kg/cm² (430 MPa).

Thus, the imposition of two factors unfavorable for ensuring the durability of the bunkers – increased loads and low temperatures – creates the conditions for the possibility of choice and application in this case of fine-grained thermally cured steel 10G2FB strength class S440. Such steel has an impact strength of 59 J/cm² [7], which in this case should be provided by the KCV⁻⁴⁰ index at a level not lower than 25 J/cm².

To assess the effectiveness of using high-strength steel 10G2FB (strength class C440), the design of the steel pyramidal-prismatic bunker is also carried out in the version made of steel of the traditional strength level (strength class C255). Evaluation of the stress-strain state, as well as verification of certain sections of the structural elements of the steel bunker, is carried out by modeling by the finite element method [8]. The design and computing complex SCAD for Windows is used [9, 10].

In a fundamental constructive solution, both versions of the bunker capacity are identical, therefore, the finite-element model of the structure is constructed and in both cases is structurally identical – **Fig. 2.**
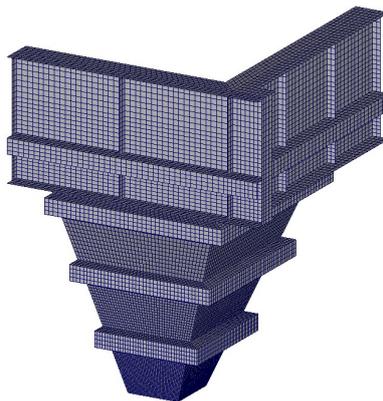

Fig. 2. The finite element model of the steel bunker

In order to be able to obtain a finite element mesh in the most stressed areas of the structure and at the same time reduce the volume of the calculations, only a quarter of the bunker structure is modeled with the corresponding conditions of strain symmetry. The final elements consisted of four-node and isoparametric plate elements of type 344. In general, the model contains about 20,000 finite elements and about 20,000 nodes, which amounted to approximately 120,000 degrees of freedom. Despite the calculations in a geometrically nonlinear formulation, such a volume is sufficient to obtain good convergence of the results at a satisfactory calculation time.

The pressure load of the bulk material is modeled as the problem of its normal and tangent component on the inner surface of the bunker sheathing and the vertical sections of the bunker beams. Let's also took into account the load from the dead weight of the structure of the bunker itself, the weight possible soundly on the super-bunker floor, the weight of the protective grill and the limit stop, as well as the weight of the vibrator. Additionally, the weight of the rear axle of the dump truck of 68 tons was taken into account, from which the capacity is loaded.

The picture of deformations of the bunker capacity in both considered variants is obtained qualitatively the same – **Fig. 3**. The deflections of the bunker beam in this case do not exceed 3 mm.
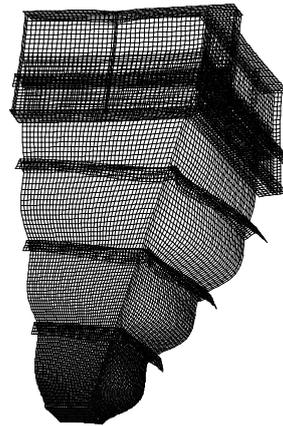
Fig. 3. The damaged state of the steel bunker (increased by 50 times)

In order to coordinate the dimensions of the bunker capacity with the planning scheme, the transverse bunker beam is shifted to the interior of the structure by 400 mm on both sides when designing the charge supply path. As a result, the width of the upper prismatic part of the structure decreased to 5.2 m with a total theoretical volume of 68 m^3.

The structural solution of the steel pyramidal-prismatic bunker with all the accepted structural solutions is finally shown in **Fig. 4**. **Table 4** shows the final section of the structural elements of the bunker and **Table 5** – weight indicators for two variants of steel of classes C255 and C440.
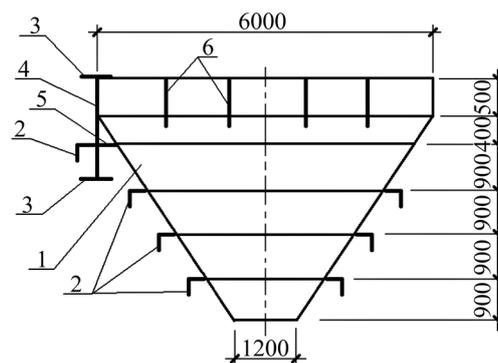
Fig. 4. The structural solution of the steel bunker:
1 – sheet sheathing, 2 – stiffeners, 3 – belts of the bunker beam, 4 – wall of the bunker beam,
5 – locking element of the nodal mount, 6 – stiffeners of the bunker beam

Thus, according to the design results, the total steel savings in one bunker capacity due to the use of 10G2FB steel of strength class C440 amounted to more than 4 tons. For the bunker compartment, which according to the project should consist of 4 structurally similar bunkers, the total theoretical steel savings exceed 16 tons, which 2019 prices are about 0.5 million UAH (about 20,000 USD). In addition, the expected additional increase in the durability of steel pyramidal-prismatic bunkers due to more efficient work on endurance at low temperatures should be noted.

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Table 4

Final sections of structural elements of the steel bunker

Structural element	Steel C255	Steel C440
Sheathing (1), mm	Plate 14	Plate 10
Stiffeners (2)	Angle 180×180×12	Angle 160×160×10
Bunker beam:		
– belts (3), mm	Plate 400×20	Plate 340×20
– wall (4), mm	Plate 1400×14	Plate 1200×10
– horizontal stiffeners (5), mm	Plate 233×14	Plate 233×10
– stiffeners (6), mm	Plate 100×14	Plate 100×10

Table 5

Weights for steel bunker design options

Mass, kg	Steel C255	Steel C440
Sheathing	7272	5324
Stiffeners	1404	1032
Bunker beam	6780	4860
Total	15 456	11 216

5. Conclusions

For the conditions of increased loads from the pressure of granular material on the design of steel pyramidal-prismatic bunkers in accordance with the design methodology, it is inexpedient for Ukraine to choose steel with increased strength. However, this technique gives fairly approximate results when assessing the stress-strain state of structures and contributes to their increased accident rate.

For the conditions of increased loads from the pressure of granular material on the design of steel pyramidal-prismatic bunkers in accordance with the European methodology, it is rational to choose steel with increased strength. This allows for a more complete use of the bearing capacity of steels. The lower limit values of such loads for steels of ordinary strength classes C255 are about 4000–5000 kgf/cm^2.

The results of the practical studies were introduced in the design of the bunkers of the by-pass track of the supply of charge materials for blast furnaces of Severstal (Canada). Theoretical steel savings due to the use of fine-grained thermally cured steel 10G2FB grade C440 exceeds 16 tons, which in prices of 2019 is about 0.5 million UAH (about 20,000 USD).

The research results on the effectiveness of steel strength improvement for steel pyramidal-prismatic bunkers in specific operating conditions can be used in official specialized regulatory documents.

References

[1] Pihnastyi, O. M., Khodusov, V. D. (2019). The Optimal Control Problem for Output Material Flow on Conveyor Belt With Input Accumulating Bunker. Bulletin of the South Ural State University. Series – Mathematical Modeling, Programming & Computer Software, 12-2, 67–81. https://doi.org/10.14529/mmp190206

[2]   Wang, XK, Xie, WB, Bai, JB, Jing, SG, Su, ZL. (2019). Large-Deformation Failure Mechanism of Coal-Feeder Chamber and Construction of Wall-Mounted Coal Bunker in Underground Coal Mine with Soft, Swelling Floor Rocks. Advances in Civil Engineering. Article ID 6519189, 16 p. https://doi.org/10.1155/2019/6519189

[3]   Bannikov, D. O. (2011). Analysis of the causes of accidents of steel capacitive structures for bulk materials. Metallurgical and Mining Industry, 5, 91–96.

[4]   DSTU-N B EN 1993-4-1:2012. Proektuvannja stalevih konstruktsij. Chastina 4-1:Silos. (2012). Natsionalnij Standart Ukraini, 179.

[5]   Structural Engineering Handbook (1997). Edited by Edwin H. Gaylord, Jr., Charles N. Gaylord, James E. Stallmeyer. – 4th ed. – McGraw-Hill, 624.

[6]   Bannikov, D. O., Kazakevitch M. I. (2002). Osnovnie prichini avarij zestkih stalnih bunkerov I nizkih silosov. Metalevi konstruktsii, 5-1, 59–66.

[7]   Hezentsvei, Yu. (2016). Tehnologichnost primenenija melkozernistih termouprochnenih staley v konstruktsiah kozuhov domennih pechey. Promislove budivnitstvo ta ingenerni sporudi, 3, 43–47.

[8]   Bean, M., Yi, S.-Y. (2019). A monolithic mixed finite element method for a fluid-structure interaction problem. Applied Mathematics and Computation, 363, UNSP 124615. https://doi.org/10.1016/j.amc.2019.124615

[9]   Fialko, S., Karpilovskyi, V. (2018). Time history analysis formulation in SCAD FEA software. Journal of Measurements in Engineering, 6-4, 173–180. https://doi.org/10.21595/jme.2018.20408

[10] Fialko, S. (2015). About parallel solvers in finite element software, oriented to shared memory multiprocessor computers. Opir Materialiv i Teoria Sporud-Strength of Materials and Theory of Structures, 94, 155–171.