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High-strength steel grades application for silos structures

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This paper deals with the work studying of high strength steel in the constructions of silo capacities. The most widespread trademarks of steel have been analyzed. Mechanical and chemical features of examples series of high strength steel of European and American manufacturers have been experimentally tested, which were used for the body's sheet panels making. It has been made checking calculation of storage capacity with the diameter of 11 m from shaped corrugated sheet of different thickness. The material for panels manufacturing is one of the researched examples of steel. It was mentioned reasonable conclusions according to the using of the concerned material for getting economically rational project decisions.

Keywords: high strength steel, vertical silo capacities, thin-walled constructions, mechanical tests

Використання високоміцних сталей для конструкцій вертикальних силосних ємностей

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Дана стаття присвячена дослідженню роботи високоміцних сталей в конструкціях силосних ємностей. Аналізувалися найпоширеніші класи сталей, які застосовуються зарубіжними та вітчизняними виробниками елеваторного обладнання при проектуванні вертикальних циліндричних силосів для зберігання зерна. Надана оцінка впливу параметрів матеріалу на властивості окремих елементів споруди. Проведено комплекс механічних випробувань на розтяг та хімічний аналіз серії зразків високоміцної сталі класів S 550 GD та S 420 GD європейських та американських виробників, які застосовуються для виготовлення гофрованих листових панелей корпусу. Числові результати досліджених характеристик підтвердили повну відповідність матеріалу нормативним значенням відповідних класів. Продовженням даного дослідження було виконання перевірочного розрахунку ємності зберігання діаметром 11 м, яка має циліндричну форму та конічне днище і виконана з профільованих хвилястих листів різної товщини. В якості матеріалу виготовлення застосовувався один з досліджуваних зразків сталі. Були отримані значення критичних факторів для листів корпусу, вертикальних ребер жорсткості і листів конічного днища силосу. Результати розрахунків підтвердили ефективність застосування високоміцних сталей при проектуванні силосних ємностей для зберігання зерна. Несуча здатність елементів була забезпечена на всіх висотних ярусах, проте резерви несучої здатності при цьому виявилися мінімальні. Відповідно проведеного аналізу сформовані аргументовані висновки, щодо використання розглядуваного матеріалу для отримання економічно доцільних проектних рішень. Зазначені конструктивні обмеження, які необхідно враховувати при проектуванні та виготовлені тонкостінних конструкцій з високоміцних сталей. В першу чергу це стосується утворення отворів під болтові з'єднання, влаштування та обробку кромок і врахування граничних розмірів внутрішніх радіусів заокруглень при гнутті деталей.

Ключові слова: високоміцні сталі, вертикальні силосні ємності, тонкостінні конструкції, механічні випробування

Introduction

Modern construction of silo capacities is developing in two directions. On the one hand, there is the development of new conceptions of shaping and economic design [1, 2], on the other, the use of high-strength steels is intensively introduced into the practice of native production. It is known because the quality of the structural material significantly affects the structure reliability, durability, its technical and economic characteristics. It is likely that such innovations have only a positive effect such as reducing of the metalwork weight, improving of performance indicators and increasing freedom in choosing design solutions. However, this step requires the designer careful consideration of the work features of the silo capacity during construction and calculation, since the elements of high-strength steel with a conditional yield curve have an increased sensitivity to strain concentrators and are prone to brittle failure.

Review of research sources and publications

Theoretical and practical research in the field of calculation and design of the thin-walled shell constructions, in particular silo capacities, does not lose its popularity. It is possible to note significant scientific works of both Ukrainian and foreign scientists [1-10]. The estimation of the reducing the metal consumption of a silo construction from high-strength steel possibility was carried out in the previous work [11].

Definition of unsolved aspects of the problem

The main elements of the vertical cylindrical container are the body, consisting of individual sheets of smooth or wavy texture, vertical stiffeners, cone roof constructions and bottom. Silos body sheets perceive axially asymmetric and asymmetric radial loads, while the stiffeners work for compression with bend. It is clear that for the supportive thin-walled shell constructions more expedient to use a material with improved durability. However, there is the question, how argumentative is the use of steel with a conditional yield curve, and whether the high utilization rate of steel is advantageous in terms of ensuring the reliability and the constructions safety.

Problem statement

The main material for making modern constructions of the silo capacities storage is steel. There are a lot of demands of mechanical and technological character to the steel, which is used for making this type of construction. The features of performance of silo capacity elements need to provide not only conditions of durability and plasticity under the influence of corrosive environment, but also the possibility of putting welded joints, bending, cutting or drilling holes. It is likely that these properties depend on the chemical composition of steel. Therefore, it is important to analyze how the type of selected steel affects the constructive and rigid parameters of the construction.

Basic material and results

In accordance with the standards of our country [12], flat products for high strength steels after the heat treatment or thermomechanical rolling is usually limited to a range of values of characteristic resistance R_{yn} of 390...590 N/ mm^2 and by index of the plasticity (the relative elongation), which is not less than 16% and for the heat treated steel $R_{yn} > 590$ N/mm^2 (the relative elongation is more than 14%).

In the most cases, foreign and native developers of elevator equipment, in the practice of designing containers for grain storage, prefer steel of European and American manufacturers. This step is argued by their better quality and by the general increase of the useful life of the construction. In addition, all constructions of the silos are subject to significant corrosion processes, therefore the galvanization of steel is a necessary condition.

For example, the German company RIELA offers products with corrugated panels of S 550 GD+Z high-alloy steel in accordance with DIN EN 10346 (value of temporary resistance when stretching is 560 MPa), with a thickness of 0,50 mm.

A number of American agro-market leaders, Agri USA (silos CHIEF), use corrugated steel panels with a tensile strength of 483 MPa and a standard galvanized covering G 115 (350 g/m^3); silos of the GSI company have a corrugated steel profile with a minimum resistance of 450 MPa, and a coating of Zincalume (55% Al, 43.5% Zn and 1.5% Si), and the thickness of 4,2...5,2 mm or galvanized steel G 90; the silo capacities of MFS are constructed of steel with a strength of 482,6 MPa, thickness to the 4,166 mm and a zinc coating of standard G 15; SCAFCO products are characterized by the use of steel with a yield strength of 393 MPa; the silos of the American manufacturer VROCK have lateral segments of the galvanized steel G 90 with the strength of up to 65 psi (448 MPa).

The Spanish companies Symaga and Cordoba offer silos made of similar structural steel S 350 GD Z 600, galvanized with the Sendzimir method and with the innovative coating of ProMag, respectively.

The prevalent Canadian silo capacities of the AGI company are made from low-carbon low-alloy steel ASTM 653, Mark 50, Class 1 with a minimum tensile strength of 450 MPa. The technical characteristics of the body sheets of silos of the Westell company indicate the use of steel with a yield strength of 345 MPa (50 ksi).

The Italian manufacturer FRAME for sheets of side walls and stiffeners uses steel with thickness of 0,8...3,5 mm, a minimum zinc coating of 450 g/m^2 and a strength of 420 MPa and the marginal displacement of 350 MPa, and also makes it possible to apply steel of a higher class with zinc coating up to 600 g/m^2.

As for the Ukrainian manufactures of steel containers for grain storage, we have the following tendency. KMZ Industries uses high-quality stainless steel of S 350 GD class with the zinc coating of Zn 275 – Zn 600 from European manufacturers S SAB, Voestalpine, Wuppermann. The silos of the company

"Variant Agro Build" also design all the main elements from Austrian galvanized steel Wuppermann Stahl GmbH of the class S 350 GD and Z 350-M-A (zinc coating of 350 g/m or 450 g/m^2 and more). The “LUBNYMASH” elevator plant, which declares the production of a silo shell from galvanized steel (275 to 450 g/m^2) of the European production of the marks S 350 GD and S 550 GD, is not an exception.

Thus, it can be noted that, for the most part, manufacturers choose the steel for storage containers that have a temporary resistance of 400 – 500 MPa. Among the strengths listed above, the Belgian Steel Arcelor Mittal S 550 GD + Z is of the highest strength. The authors` team has already carried out the calculation of silo constructions with a diameter of 22 m from such steel, followed by a detailed analysis of the bearing capacity of the main elements [11]. The results showed that the use of steel of this trademark really enabled to reduce the thickness of the elements, but at the same time it caused a significant deterioration of the rigid characteristics of the vertical stiffening edges and increased deformability in the constructions of the roof and the bin-top gallery.

Check of the used material correspondence to the requirements of the standard UNSS EN 10346 [13] was this study continuation. A set of mechanical tests for the stretching of 6 standard flat examples of European steel S 550 GD (Fig. 1-a) provided by the "LUBNYMASH" company was made and their chemical analysis was carried out. The experiments were carried out on the basis of the certified laboratory of mechanical tests LLC "Etual-Metal".

a)

b)

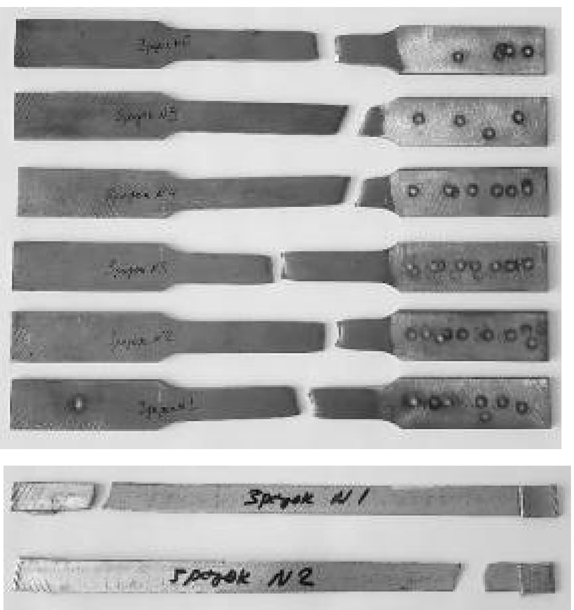


Figure 1 – Examples of the steel after the destruction:
a – European steel;
b – steel of the USA manufacture

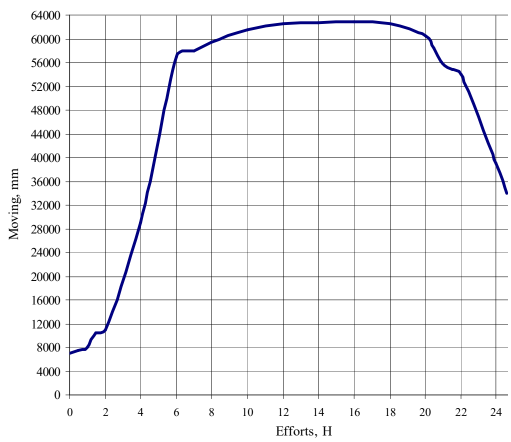
According to [13], the steel S 550 GD (steel number is 1.0531) has the following mechanical properties: the conditional yield curve is $R_{yn,0.2}$ = 550 MPa, the temporary resistance is R_{un} = 560 MPa, and the relative elongation is not given. Accordingly to the melting analysis, the chemical composition of the steel of S 550 GD class should be C = 0,20%, Si = 0,60%, Mn = 1,70%, P = 0,10%, S = 0,045%.

Mechanical tests on the static stretching were carried out at the hydraulic tensile-testing machine P-50 M2 (Armavir, Russia) with a built-in electronic remote control, accordingly to the GOST 1497-84 [14]. The chemical analysis of metal examples was carried out by using an optical emissive spectrometer Q2 ION (Bruker Elemental GmbH, Germany).

The numerical results of the features research (Table 1) showed that the provided steel examples fully correspond to the specified trademark

Table 1 – Check report of mechanical tests on the static stretching

The results f the research and the diagram of stretching (for the example №1)			
№of the examle	Max. efforts, H	Ultimate strength, Н/мм^2	Relative elongation, %
1	63489,299	793,616	8,223
2	**63242,549**	**790,532**	8,057
3	63686,457	796,081	8,687
4	63715,082	796,439	7,637
5	64203,062	802,538	**7,227**
6	63579,683	794,746	8,187

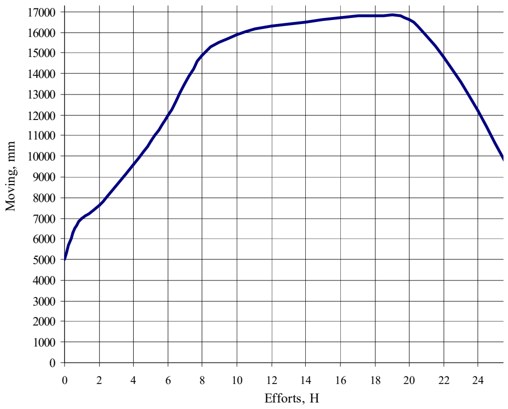


The second stage of the research was the similar tests of increased strength steel of S 420 GD class, accordingly to EN 10346:2015 of the USA manufacture, and used by the GSI company for the construction of vertical steel capacities for grain storage. The examples were made directly from the sheet of sheathing of the silos (Fig. 1-b). The numerical results of mechanical tests on the static stretching are given in the Table. 2.

It is important to note that, in accordance with the guidelines [12], the calculation of the body sheets and the vertical stiffeners of the silo capacities from the steel S 550 GD ($R_{yn,0.2}$ = 550 MPa, R_{un} = 560 MPa) must be made on the strength with additional coefficient of reliability, according to the material γ_u = 1.3 with the using of calculation resistance R_u, which is determined by the temporal resistance under the stretching R_{un}. Besides, when determining the calculation resistance R_u, it is necessary to consider the coefficient of reliability, accordingly to the material γ_m = 1.05, i.e. $R_u = R_{un} / \gamma_m$. Thus, the actual calculated characteristic of the silo element transverse section strength from the steel S550GD is not 560 MPa, but $R_u / \gamma_u \approx 410$ MPa.

Table 2 – Check report of mechanical tests on static stretching

The results f the research and the diagram of stretching (for the example №1)			
№ of the example	Max. efforts, H	Ultimate strength, H/мм^2	Relative elongation, %
1	**16764,448**	**827,874**	**8,481**
2	17103,400	844,612	9,428



Instead, the steel S 420 GD, according to UNSS EN 10346:2014 [13] has the following mechanical features: the conditional yield curve is $R_{yn,0.2}$ = 420 MPa, the temporal resistance is R_{un} = 480 MPa MPa, and the relative elongation is δ = 16%. Accordingly to the instructions [12], for steel with the characteristic resistance of $R_{yn} \leq 440$ MPa, the strength calculation is performed accordingly to the calculation resistance beyond the yield strength R_y and with considering the coefficient of reliability, accordingly to the material γ_m = 1.025. Thus, the calculation resistance is $R_y = R_{yn} / \gamma_m \approx 410$ MPa.

GSI silo testing, which has a cylindrical shape, a conical bottom and made of steel grade S 420 GD, has also been performed. Nominal diameter of the container is 11 m. Constructively the body shell consists of shaped wavy galvanized sheets with the height of 1165 mm (hereinafter, all geometric sizes were set by the measurements). The height of the silo consists of 14 panels. Their thickness has three standard sizes: 0,85 mm are I-VII tiers; 1,2 mm are VIII-XII tiers and 1,36 mm are XIII-XIV tiers. Separate sheets are connected with M10 bolts, which have sealing elements of the strength class 10.9. In the ring direction, the bolts are chequer. Total number of bolts per tier is 48 pcs. The outer stiffeners (Fig. 2) are made of a curved profile of a trapezoidal shape with 210 mm in width and 70 mm in height. The thickness of the transverse section of the rib varies within 1,2...4,2 mm and decreases in height. The conical bottom is formed of three layers of flat sheets with a thickness of 2 mm.

a)

b)

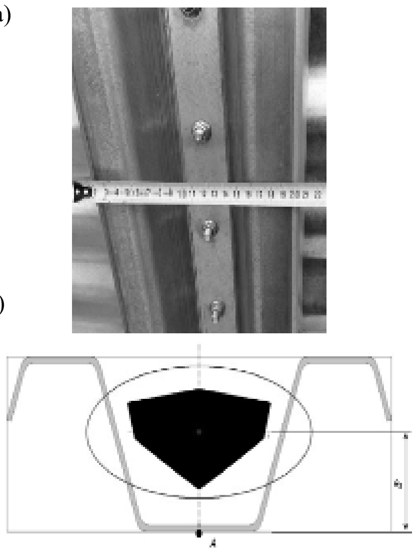
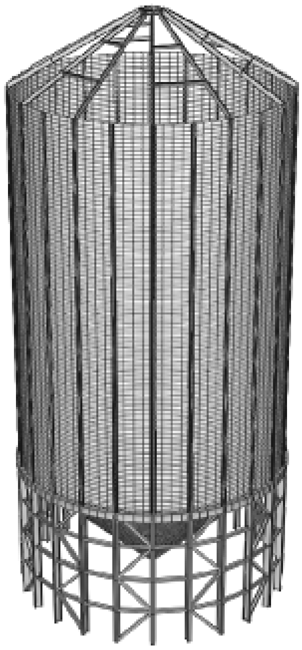


Figure 2 – Vertical stiffeners:
a – general view; b – transverse section with the orientation of the main axes

The mathematical) silo model (Fig. 3) was created in the finite element program complex SCAD 21.1 and included the following groups of constructive elements: 1 – pier column; 2 – braces and spacers of the pier column; 3 – supportive ring of the rigidity of the conical bottom; 4 – bottom sheets; 5 – vertical stiffeners; 6 – body sheets; 7 – elements of the conical roof. Each finite element of the model was characterized by the following main features: a dimension of the space used (one-dimensional, two-dimensional, three-dimensional); a set of nodes, which are located at the boundary between the elements and which are common for the boundary elements; a set of external and internal degrees of freedom in the nodes of the elements; a system of approximation functions.

The compilation correctness of the silos calculation model and the correspondence of calculation results with the actual work of structures at each step was controlled by the following tests: the dimension of the input and output quantities; the nature of the dependence of the result from the change of some input data, including the check of such properties as the expectation of symmetry (asymmetry) or insensitivity to some parameters; the system behavior under the extreme values of parameters; the observation of the conclusions, which are made from the theorems of reciprocity.

The calculation results have shown that the bearing strength of the body sheets (numerical data are given in the Table 3), bolted joints, stiffeners (Table 4) and other elements of the silo capacity is provided on all high-rise tiers, however, at the same time reserves of bearing strength are minimum: for body sheet of the 7th tier the critical factor is of 0.817; for the vertical stiffeners of the 12th tier the critical factor is of 0.973, for 13th is of 0.916, for 14th is of 0.983; for the sheets of the upper tier of the conical bottom the critical factor is of 0.71.

a) 

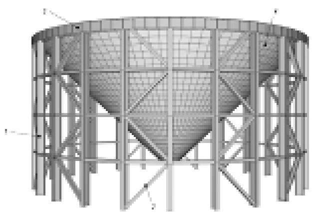
b) 

Figure 3 – Finite-element model of silo capacity:
a – general isometric appearance; b – the support part

Table 3 – Critical sheet factors of the body of silos

Tier	t_w, mm	N_{cr}, kN	σ_{cr}, kN/sm^2	K_R
1	0,85	58	6,8	0,208
...				
7	0,85	228	26,8	**0,817**
8	1,2	247	20,6	0,628
9	1,2	265	22,1	0,673
10	1,2	281	23,4	0,714
11	1,2	296	24,7	0,752
12	1,2	310	25,8	0,787

Symbols: t_w is the thickness of the body sheet of the silos at a given level;

N_{cr} is the value of the calculated annular longitudinal effort of force per unit of height from the horizontal pressures of bulk materials in the walls of round steel silos, considering additional efforts from temperature's drops;

$K_R = N_{cr} / (R_y\ t_w) \cdot \gamma_{neto} \le 1$;

$R_y = 41$ kN/sm^2 are a calculation resistance of steel beyond the yield stress;

$\gamma_{neto} = 1.25$ the coefficient of weakening of the transverse section by the holes of bolted joints, accepted on the basis of the analysis of technical documentation.

Table 4 – The bearing capacity calculation of the vertical stiffeners

Tier	t_w, mm	W_n, sm^3	N_m, kN	M_m, kN·sm	K_R
10	2,8	16,373	183	251	0,849
11	3,4	19,638	210	326	0,856
12	3,4	19,638	239	370	**0,973**
13	4,2	23,862	269	436	**0,916**
14	4,2	23,862	300	486	**0,983**

Symbols: W_n is a minimum moment of resistance relative to axis V (see the Drawing 2);

N_m, M_m are respectively, the longitudinal force and bending moment from the external load;

$K_R = \gamma_d\ (N_m\ /\ (A_p\ R_y\ \gamma_c) + M_m\ /\ (W_n\ R_y\ \gamma_c)) \le 1$ is the value of the critical factor;

γ_d is the coefficient of reliability of the model, which considers the uncertainty of the calculation scheme and other similar circumstances in the form of the constructions sensitivity to local destructions, to initial imperfections, to the joints compliance influence, to the plastic properties of the material, to the presence of dynamic effects or to idealizing of a material work diagram;

A_p is a cross-sectional area of the stiffeners;

$\gamma_c = 1.0$ is a coefficient of working conditions of the constructions.

Table 5 – Calculation of the bearing capacity of the conic bottom sheets

Tier	N_h, kN	N_T, kN	σ_h, MPa	σ_T, MPa	σ_Σ, MPa
upper	624	533	312	267	292
middle	461	370	231	185	212
bottom	270	204	135	102	122

Symbols: N_h, N_T are the boundary calculation values of longitudinal forces (correspondingly horizontal and along the formative) per unit length of the conic bottom section;

σ_h, σ_T are a strain in the sheets of the conical bottom in the ring and axial directions, respectively;

$K_R = \sigma_\Sigma / R_y$ is a value of the critical factor.

Another important factor is considering when designing thin-walled constructions of high strength steels is a number of constructive constraints, which are connected with the installation of holes under the bolted joints. According to the requirements [15], the holes for bolted joints must be formed by drilling, punching, gas-thermal or plasma cutting; thus the formation of holes using the method of punching is prohibited for steels with a yield strength of more than 350 MPa. Also, the steel part edges of class C 440 and above are subjected to planning or milling. According to the clause 9.14 [15], when bending parts of carbon steel on bending presses, internal radius of rounding are assumed to be not less than $1,2t$ for constructions that perceive static load. For parts made of low-alloy steel (constructive steel S 550 GD should be considered in this case as a low-alloyed), the boundary size of internal radius of rounding should be 50% higher than for carbon steel.

The last argument considered when choosing a steel trademark for the manufacture of a silos construction is the coefficient of material use $k_{yu} = R_y / R_u$, which characterized by the ratio of yield strength R_y to temporary resistance R_u (strength limit). For the steel trademarks considered, this value is almost equal to one $k_{yu}^{S550GD} \approx 0.98$ [11], $k_{yu}^{S420GD} \approx 0.88$. The reserve of bearing strength of the constructions made of high-strength steels with such a coefficient value k_{yu} is rather little. It should be considered that, first of all, the destruction of constructions is fragile (quick, we can also say, instant); secondly, the deflected mode of constructions is extremely dependent on the presence of strain concentrators in the form of holes, distortions of the elements shape (including bending), damages of the manufacture, i.e. any factors, which form the construction, that are unfavorable for flowing of the power flows.

Conclusion

1. Calculations of silo constructions made of high-strength steels confirm the high efficiency of this material when designing silo capacities for grain storage.
2. Checking calculation of the silo capacity elements, made of the S 420 GD steel, even when the thickness of flat products is approximate to 1 mm (the minimum thickness of the body sheets is 0,85 mm, of the stiffeners is 1,2 mm and of the bottom is 2 mm), is provided at every high-rise level, but the reserves of the bearing strength is minimal.
3. There are a number of constructive constraints that must be considered when designing thin-walled constructions of the high-strength steel. First of all, this applies to the requirements for holes, edges and bending of parts.
4. Experimental tests of the steel chemical composition and properties of European and American manufacturers showed full correspondence to the normative values of the respective trademarks. However, in spite of the improved strength characteristics of the S 550 GD steel in comparison with the S 420 GD, in accordance with the guidelines [12], the numerical values of the actual design characteristics of the transverse section elements of the silo capacity of both steel types must be chosen identically.

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