Doi: 10.33644/01005

УДК 624.046.3.:624.014.27.:624.074.4:725.36

LISENYI O.M.
PhD in Eng., Head of Department, State Enterprise "The State Research Institute of Building Constructions",
Kyiv, Ukraine,
e-mail: lab343@ndibk.gov.ua
tel. +38(044) 249-37-66
ORCID: 0000-0003-0792-8082

LIUBCHENKO I.H.
PhD in Eng., Assoc. Professor, State Enterprise "The State Research Institute of Building Constructions",
Kyiv, Ukraine,
e-mail: i.lubchenko@ndibk.gov.ua
telл. +38 (097) 494-13-45
ORCID: 0000-0002-3329-4725

SLYUSARENKO, Yu.S.
PhD in Eng., Senior Researcher, Deputy Director for Scientific Work, State Enterprise "The State Research Institute of Building Constructions",
Kyiv, Ukraine,
e-mail: slus@ndibk.gov.ua
tel. +38(044) 249-38-83
ORCID: 0000-0002-0447-3927

STEEL CIRCULAR SILOS FOR GRAIN

ABSTRACT

In Ukraine the thin-walled steel silos for grain storage have been erected by the domestic and foreign producers. Silos for grain have the complicated structural system, the basic constituents of which include the cylindrical body of corrugated steel sheets supported by vertical and circular ribs, and the conical roof of flat steel sheets on bent sheets beams. The silo body is a cylindrical orthotropic shell and its design peculiarities are not sufficiently revealed in national regulations. The European codes contain more detailed recommendations for the modern steel silos design with regard to both the design technological loads determination and the bearing strength calculations. However, being practically applied for computing the silos strength and stability, the Eurocodes create a number of substantial problems. During the operation of silos built in recent year the accidents frequently occur reflecting the design and operation shortcomings.

In NDIBK the improvement of steel silos design methodology has been carried out with the adaptation of some approaches implemented in the EU codes and under observance of general conformity to the building norms of Ukraine. The equivalent membrane properties and equivalent bending properties of corrugated sheets, including tensile stiffness and bending stiffness, respectively, are determined. Based on these properties the equivalent moduli of elasticity are found for the orthotropic shell finite elements by two mutually perpendicular directions of shell surface. The necessity is justified for the preproduction models and full-scale objects experimental studies and researches with an aim of determining the resistance specifications of multi-bolt joints of the shell galvanized corrugated sheets. The attention is drawn to the fact that the application of friction connections with small diameter bolts promotes the long-term reliable operation of the silos, but for their use ensuring the national building regulations shall be improved. The mechanical and deformation specifications of corrugated profiles require an experimental verification as well.

KEY WORDS: Steel silo, silos destruction, corrugated sheet, orthotropic shell, strength, bolt joints

СТАЛЕВІ ЦИЛІНДРИЧНІ СИЛОСИ ДЛЯ ЗЕРНА

АНОТАЦІЯ

В Україні тонкостінні сталеві силоси для

зберігання зерна зводяться вітчизняними та закордонними виробниками. Силоси для зерна мають складну конструктивну систему, основними складовими якої є циліндричний корпус з гофрованого сталевого листа, підкріплений вертикальними і кільцевими ребрами, та конічний дах з плоского сталевого листа на балках з гнутого листа. Корпус силосу є циліндричною ортотропною оболонкою, особливості проектування якої у вітчизняних нормах розкриті недостатньо. Європейські норми містять більш детальні рекомендації з проектування сучасних металевих силосів як у частині визначення розрахункових технологічних навантажень, так і щодо розрахунків несучої здатності, однак при практичному застосуванні Євронорм при розрахунку міцності і стійкості силосів виникає ряд суттєвих проблем. При експлуатації збудованих в останні роки силосів мають місце непоодинокі аварії, в яких проявляються недоліки проектування та експлуатації.

В НДІБК здійснено удосконалення методики розрахунку сталевих силосів з адаптацією окремих підходів, прийнятих у нормативних документах ЄС, при дотриманні загальної відповідності нормам України. Визначені еквівалентні мембранні властивості гофрованого листа – жорсткість на розтяг, та еквівалентні згинальні властивості – жорсткість на згин, за якими визначені еквівалентні модулі пружності для скінченних елементів ортотропної оболонки за двома взаємно перпендикулярними напрямами поверхні оболонки. Обгрунтована необхідність проведення експериментальних досліджень на дослідних зразках і натурних об'єктах та досліджень з метою визначення характеристик опору багатоболтових з'єднань гофрованих оцинкованих листів оболонки. Звернута увага, що застосування фрикційних з'єднань на болтах малих діаметрів сприяє довготривалій надійній роботи силосу, але їх використання потребує удосконалення національних будівельних норм. Також потребують експериментальної перевірки механічні та деформаційні характеристики гофрованих профілів.

КЛЮЧОВІ СЛОВА: сталевий силос, руйнування силосів, гофрований лист, ортотропна оболонка, міцність, болтові з'єднання.

THE GRAIN SILOS DESIGN AND OPERATION

From time to time the grain silos destructions occur. Only in 2018 there were some such cases. Roman Shtelmach, the Technical Director of KMZ Industries, points out a broad enough list of silos destruction causes: from the design stage errors to malfunctions or due to production defects to force majeure [1]. He notes that the selection of equipment that does not meet the operation site and conditions requirements, the design errors or manufacturing defects (mismatch of construction or design documentation) become evident immediately after the object commissioning. And when the silo operates more than one year, the most probable causes of its "collapse" are the human factors.

Reviewing the statistics of the silo accidents causes, Anatolii Butenko, the Director of Trans Stroy Complex, points out that among the accidents causes the unsuccessful design solutions occupy 25.1% and the design rules defects - 4.0% [2].

The foreign production silos do not always meet the operation conditions in Ukraine taking into account the local climatic conditions. The designers of Ukraine mainly adapt the existing ready technological projects developed in the USA or Europe. In such cases, the silos designing intricacies remain largely unknown, and their strength calculation is a trade secret.

As site https://inshe.tv/nikolaev/2017-08-16/256604/ reported [3], at the Kostiantyniv elevator having the grain storage total volume of 100 000 tons (Figure 1) in two months after erection on 16.08.2017 one of the Turkish production silos was deformed and destructed (Figure 2).

A commission with the involvement of the enterprise, design organizations, installation companies and manufacturing plant representatives was convened at the enterprise to establish the accident cause.

The newspaper (https://www.2000.ua/ 08/16/2017) posted a video that traces the silo destruction nature as an important full-scale experiment (Figure 3).

A number of reasons mainly causes accidents. The problem of silos crashes preventing relates not only to the representatives of the company, design and installation companies and silos manufacturers. This is a state problem, because the foreign manufacture silos must be checked by calculations for compliance with national construction standards.

Accidental situations result from using the simplified

Figure 1 - Kostiantyniv elevator for grain storage

Figure 2 - Grain silo destruction consequences

Figure 3 - Segment of video recording the silo deformation and destruction beginning

silos calculation methods, which do not fully reflect the silo design features and do not exhaustively assess the members bearing capacity. The durability, reliability and safety of silos operation can be ensured only through the actual operation studies and the improvements of the grain storage facilities design standards.

The design of grain storage facilities, including the metal silos, is governed by the code DBN V.2.2-8-98 [4], which does not envisage the use of thin-walled corrugated profiles for the silo body erection. From 01.07.2013 the standard DSTU-N B EN 1991-4:2012 [5] is in force in Ukraine. It contains the general principles and guidelines regarding the actions determination for calculating the bulk materials storage structures, including the grain storage steel silos. This standard shall be applied in conjunction with a number of DSTU-N B EN status standards, i.e. the silos must be designed according to European standards. The DBN V.2.2-8-98 and DSTU-N B EN 1991-4:2012 requirements comparison shows that the structures analysis is based on the application of the well-known Janssen's equation to determine the forces in the silos walls from filling with bulk materials. There are also some differences between these standards in the consideration of the various cereals specific gravity, friction factors and local grain influences. DSTU-N B EN 1991-4:2012 shows a rolling profile of circular panel sheets, which may be interpreted by sinusoidal corrugations (Figure 4) with the determination of the corrugated wall friction factor. However, when designing a silo according to DBN B.2.2-8-98, the allowance for the effective friction factor on corrugated walls would be incorrect, because such friction factor is defined in the requirements complex of a number of European regulations.

For corrugated steel sheets, the walls friction effective factor should be determined by the formula:

$$\mu_{eff} = (1 - a_w) \tan \varphi + a_w \mu;$$

where φ is the angle of internal friction; μ is a friction factor on flat surface; $a_w = 0.2$ is a factor of grain contact with a wall for the

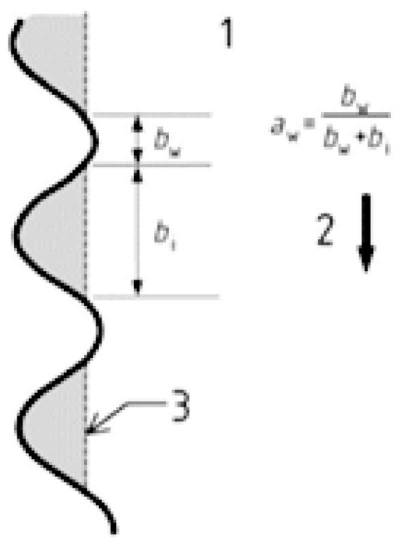

Figure 4 - Profile with sinusoidal corrugations: 1- bulk material; 2- material flow; 3- surface discontinuity

sinusoidal corrugations.

According to DBN V.2.2-8-98 for wheat grain the internal friction angle is φ = 25° and for a silo flat steel surface the grain friction factor is f = 0.4, and according to DSTU-N B EN 1991-4: 2012 the internal friction angle is φ = 30° and for a silo flat metal surface the grain friction factors are f = 0.38 for galvanized steel and f = 0.57 for carbon steel. The effective factor for the friction on galvanized steel sheets corrugated surface will be:

$$\mu_{eff} = (1- a_w) \tan \varphi + a_w \mu = (1 – 0.2) \tan 30° + 0.2 \bullet 0.38 = 0.538.$$

The variations in friction factors determination according to DBN B.2.2-8-98 and DSTU-N B EN 1991-4: 2012 cause a significant difference in the determination of the loads and forces in the silo body due to grain filling. Since the DBN status is higher than the DSTU-N status, for the DSTU-N B EN 1991-4: 2012 provisions application it is necessary to introduce the DBN V.2.2-8-98 amendments based on the experimental and theoretical studies. The development and improvement of the national regulatory framework for the grain metal silos designing is necessary.

CALCULATION OF SMVU TYPE SILOS

In NDIBK the method for the SMVU steel silo design according to TU U 0397047.001- 2000 [6] was developed based on the three-dimensional computational model and finite elements method with the LIRA-CAD software use. The silo design is performed within the framework of the elastic members operation, which is the first approach to the study of the silo structure actual operation. The LIRA software package allows to reflect the actual silo members' geometric specifications and to take into account the peculiarities of the joint operation of the steel silo body and reinforced concrete foundation. The three-dimensional computational model includes the wall orthotropic shell elements, stiffeners, roof and reinforced concrete foundation. The silo members carrying capacity and deformability are calculated for the silo body versions made of different grades steels.

The steel silos design methodology was developed with the adaptation of individual approaches accepted in the EU codes and the observance of conformity to the Ukrainian standards. In particular, the silo members stress condition determination features, which did not depend on national standards, were taken into account based on the provisions of DSTU-N B EN 1993-4-1: 2012 [7]. The provisions for determining the corrugated sheet shell stiffness characteristics, assessing the strength and limiting the silo members deformation were taken from this standard.

The silo body corrugated sheets are considered as an equivalent homogeneous orthotropic shell with sinusoidal corrugations. The equivalent membrane properties of the corrugated sheets, i.e. tensile strength, and the equivalent bending properties, i.e. bending stiffness, are determined. Based on the corrugated sheets equivalent stiffness characteristics, the equivalent moduli of elasticity for the orthotropic shell finite elements are determined taking into account that in the common structural analysis programs (LIRA, SCAD) for the orthotropic shell members two moduli of elasticity are specified for two mutually perpendicular directions in the shell plane. These two moduli are determined depending on the principal task of the design, i.e. for the reliable determination of the membrane components of the shell stress condition and in the case of the determining influence of bending components.

The SMVU type silos are designed for two groups of limit states as follows:

- the first group (destruction, loss of stability etc.);
- the second group (excessive displacements).

The silo steel members are calculated according to the following conditions:

- the members strength,
- the nodes strength,
- the local members stability,
- the total silo stability,
- the support units and anchors strength, and
- the silo deformations restriction.

The results novelties include the computational determination of the corrugated plate axial stiffness, the silo stress conditions comparison in the cases of uniform grain loading and asymmetric loading with lateral discharge, the comparison of the body main members load-carrying capacity if they are made of different grade steels, and the assessment of foundations tilts dependence on soil conditions and various types foundations of the circular silos.

Further development of the computation method requires the calculation principles experimental check on models and full-scale objects.

SILO MEMBERS BOLT CONNECTIONS

The SMVU type silo members connections are performed with bolts M10 grade 8.8. There are more than 50 thousand bolts in the SMVU 220.100 silo body. The silo body reliability and durability depend on the bolt connections quality. Roman Shtelmach [1] draws attention to the fact that in real life the silo strength issues are addressed only after accidents, and notes that anarchy and technical ignorance prevail in the bolt connections and assembling solutions for the silos steel structures. Some companies establish the appropriate services and train the qualified field engineers. He advises that those who already have elevators should check the quality of bolt tightening at least once a year. Such proposal proves that the clear instructions for assembling the silo bolt connections are not available now.

Calculation of bolt joints according to DBN V.2.6-198:2014 [8] is simple enough, the bolts are checked for shear by the bolt steel strength and for bearing by the strength of steel sheets that are connected, but the problem of the connection tightening degree remains open.

The SMVU 220 silo body ring is assembled of 24 panels. When bolt joints act in bearing, the gap between M10 bolt and 12mm diameter hole in the sheet will be eliminated. In the limit state, when all bolt joints act in bearing, the silo perimeter may be increased. If we consider that the bolts on the average are placed in the holes centers, the silo perimeter increase will be $24x^2 = 48$ mm or more, taking into account the steel crushing.

In the cases of the bolt joints operation in bearing and alternating full loading and unloading of the silo, the gaps between the bolts and holes in the sheets will be eliminated, the bolts will gradually be involved in the operation and will crush the sheets steel, and the silo body will become deformed. To ensure the silo long-term reliable operation it is necessary to prevent the bolt connections operation in bearing.

Prior to the ring panels sheets crushing, the connection will act as slip-resistant. Sheets with one friction plane have less bearing capacity in the case of a friction connection than in sheets crushing.

The explanation given by some silos designers and manufacturers that paired sheets for ring panels are used in the absence of the required thickness sheets or to increase the bolts shearing planes number can be considered unsatisfactory. High-strength bolts of grade 8.8 have a sufficient margin of shear strength for one shear plane, and the sheets nomenclature allows the vast majority selection of ring panels from single sheets.

The frictional joint surfaces number increases with the use of paired sheets. The ring panels of two folded sheets have three times the friction connection strength than the friction connection of the single sheet ring panels, and significantly greater strength of the friction connection than in sheets bearing.

The behavior of friction joints with M10 bolts is not taken into account, because the national regulatory framework of the construction industry envisage the M16 bolt minimum diameter for friction connections. In industry the friction connections with the bolts of smaller diameters are used. It is possible that the pioneer developers of the silo structures from thin-walled corrugated profiles took into account the bolts tightening to the friction connection state.

In the near abroad it is possible to design the frictional connections with M12 bolts, for instance, in Belarus the EN standards are implemented and the Russian Federation its has own code SP16.13330.2017 [9].

In DBN V.2.6-198:2014 [8] it is stated in para 6.2.6 that "For steel frictional joints, the high-strength 40X steel "Select" bolts with a temporary resistance of not less than 1100 N/mm^2 in the cold specification version according to GOST 22356 should be used. It is allowed to use bolts and nuts according to other normative documents with ensuring the requirements for the adopted strength grade according to GOST 22356". In accordance with GOST 22356 the bolt minimum diameter is 16 mm. This means that, according to DBN V.2.6-198:2014, the high-strength bolts M12 grade 8.8 cannot be used for friction joints in accordance with the interstate standard GOST 32484.3-2013 being in force in Ukraine [10]. We think that DBN V.2.6-198:2014 must be improved.

The friction connections eliminate the deformation of the silo body perimeter and diameter and contribute to the long-term reliable silo operation. But it is advisable to experimentally test the behavior of the silo elements bolt connections.

PROPOSALS FOR THE SILOS DESIGN METHODS IMPROVEMENT

The urgency of the silos calculation and design methods improvement arises from:

- lack of experience in the calculations of a silo as an orthotropic shell supported by ribs;
- need to experimentally verify the justification of the calculation methods used in DSTU-N B EN 1993-4-1:2012 [7];
- direct analogues absence for some design coefficients in national regulations.

Work must be carried out in the following directions:

1) validation of the silo strength and stability calculations and their comparison with the corresponding results obtained with the three-dimensional computer models, especially taking into account the wind effects on empty silo, lateral unloading etc. for asymmetrical loading;
2) determination of the silo stressed state actual specifications by the prototypes and full-scale objects experimental tests and the comparison of the experiment results with the calculations;
3) experimental determination of the multi-bolt joints resistance specifications for the shell galvanized corrugated sheets, including such joints deformability in a near-limit state;
5) experimental determination of mechanical and deformation specifications of corrugated sheet made of steels not covered by DBN V.2.6-198:2014 [8];
6) development of the stability and seismic impact calculations procedures;
7) generalization of steel silos calculating and engineering experience at the level of an "enterprise standard" manual with its further development to the state standard level;
8) DBN V.2.2-8-98 revision on the basis of experimental and theoretical researches;
9) silo calculation methods formalization and algorithmization for an independent application by the design specialists.

CONCLUSIONS

1. Taking into account the corrugated sheet membrane properties, the equivalent elasticity moduli for two directions of the orthotropic shell surface are determined and the silo body design method is improved.
2. The necessity is substantiated to carry out the prototypes and full-scale objects experimental researches in order to improve the regulatory framework of grain metal silos designing.
3. The need is shown to determine the strength of multi-bolt joints of shell corrugated galvanized sheets and to develop the regulatory framework for the design of the small diameter bolts friction connections.

БІБЛІОГРАФІЧНИЙ СПИСОК

1. Штельмах Р. Чтобы не повторилось, или еще раз о падении силосов. URL: https://elevatorist.com/blog/read/511-chtobyi-ne-povtorilos-ili-esche-raz-o-padenii-silosov
2. Бутенко А. Уроки аварий стальных силосов. URL: https://elevatorist.com/blog/read/323-uroki-avariy-stalnyih-silosov
3. На Константиновский элеватор вызвали турков – искать виновных в обрушении емкости с зерном. URL:https://inshe.tv/nikolaev/2017-08-16/256604/
4. ДБН В.2.2-8-98 Підприємства, будівлі і споруди по зберіганню та переробці зерна.
5. ДСТУ-Н Б EN 1991-4:2012 Єврокод 1. Дії на конструкції. Частина 4. Бункери і резервуари (EN 1991-4:2006, IDT).
6. ТУ У 30397047.001-2000 Силоси металеві уніфіковані типу СМВУ. Технічні умови.
7. ДСТУ-Н Б EN 1993-4-1:2012 Єврокод 3. Проектування сталевих конструкцій. Частина 4-1. Силоси (EN 1993-4-1:2007, IDT).
8. ДБН В.2.6-198:2014 Сталеві конструкції.
9. ГОСТ 32484.3-2013 (EN 14399-3:2005) Болтокомплекты высокопрочные для предварительного натяжения конструкционные.
10. СП 16.13330.2017 Стальные конструкции.

REFERENCES

1. Shtelmakh, R. (2019). Not to be repeated, or again about the fall of silos. Retrieved from https://elevatorist.com/blog/read/511-chtobyi-ne-povtorilos-ili-esche-raz-o-padenii-silosov
2. Butenko, A. Lessons learned from steel silos accidents. Retrieved from https://elevatorist.com/blog/read/323-uroki-avariy-stalnyih-silosov
3. The Turks were called to the Konstantinovskii elevator - to look for those responsible for the collapse of the tank with grain. Retrieved from https://inshe.tv/nikolaev/2017-08-16/256604/
4. Enterprises, buildings and structures for the storage and processing of grain: DBN V.2.2-8-98.
5. Eurocode 1. Actions on structures. Silos and tanks (Part 4): DSTU-N B EN 1991-4:2012 (EN 1991-4: 2006, IDT). (2013).
6. Silos metal ventilated of SMVU type. Specifications: TU U 30397047.001-2000.
7. Eurocode 3: Design of steel structures. Silos (Part 4-1): DSTU-N B EN 1993-4-1:2012 (EN 1993-4-1:2007, IDT). (2013).
8. Steel structures. Design code: DBN V.2.6-198:2014. (2015).
9. High-strength structural bolting assemblies for preloading. System HR-hexagon bolt and nut assemblies: GOST 32484.3-2013 (EN 14399-3:2005). (2015).
10. Steel structures: SP 16.13330.2017. (2017).

Стаття надійшла до редакції 16.12.2019 року