На прикладі тестової задачі досліджуються особливості впливу різних чинників на напружено-деформований стан складених тонкостінних конструкцій із болтовим з'єднанням окремих елементів. Прикладом таких конструкцій є металічні зерносховища – силоси, які складаються із панелей, що з'єднуються болтами. Тестова конструкція містить дві вузьких плоских смуги, з'єднаних внакид. У отвори в цих смугах розміщений болт із попереднім затягуванням. Ураховується тертя і проковзування смуг і болта, контакт бічної поверхні болта і отворів, а також взаємний вплив вигину і розтягування. Таким чином, у моделі враховані геометрична, фізична і структурна нелінійності. Система піддається дії поперечного навантаження, яке прикладене до однієї сторони смуги. Моделюється поетапне навантаження систем. Встановлено, що при навантаженні досліджувана система набуває прогин, який нерівномірно зростає з ростом навантаження. Це зумовлено тим, що на нього впливає і пружна деформація смуг, і взаємне проковзування в зоні з'єднання. При остаточному вибиранні зазору між болтом і отворами в панелях відбувається переважно пружне деформування системи. Після першого розвантаження в системі установлюється залишковий прогин. Також встановлено, що у системі діють поздовжні зусилля, які можуть бути набагато більшими від поперечних сил від навантаження. Характерним є сильний взаємний вплив вигину і розтягування смуги. У результаті досліджень встановлено чинники, що визначають напружено-деформований стан дослідженої системи: геометрична нелінійність, контактна взаємодія, тертя і проковзування, зв'язаність вигину і розтягування. Таким чином, без урахування всіх цих чинників розрахункова модель для подібних тонкостінних конструкцій буде неадекватною, результати розрахунків із її застосуванням матимуть значні похибки, а рекомендації – недостовірними. Здійснені дослідження дають можливість розроблення більш адекватних моделей для аналізу реакції складених тонкостінних конструкцій на дію навантаження

Ключові слова: тонкостінна конструкція, болтове з'єднання, напружено-деформований стан, металічне зерносховище, геометрична нелінійність

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THE STUDY OF MULTICOMPONENT LOADING EFFECT ON THIN-WALLED STRUCTURES WITH BOLTED CONNECTIONS

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1. Introduction

Thin-walled structures have become widespread in practice. They include a wide variety of composite structures which in many cases consist of plain or corrugated panels connected with high-strength bolts. In particular, metal granaries (silos) are typical examples Silos are subjected to the effect of a system of operating loads including effects of wind, rain, snow, temperature fluctuations, etc. At the same time, internal pressure from grain, bulk material or liquid is the main load. Accidents often occur as a result of failure of silo elements under action of operating loads. In many cases, such failures occur in places of bolted connection of panels. These problems cannot be predicted with the use of traditional continuous strip shell models because impact of bolts on stress-strain state (SSS) of the studied structure is not taken into account. Existing models of such connection do not take into consideration all factors effecting SSS of such composite structures. Accordingly, existing models require further development and improvement. Therefore, let us consider composite structures and methods for calculating them on an example of silos.

Relevance of the study in this direction is determined by the lack of models of analysis of behavior of thin-walled structures with bolted connections under action of multi-component loads.

2. Literature review and problem statement

Silos are widely used in present-day industry due to their advantages: ease of assembly, reliability, low cost operation, easy maintenance, etc. However, as practice shows, a number of problem situations occur in operation that lead to structure failure [1]. Main failure causes include loss of stability of bearing elements and walls, emergence of unwanted deformations in difficult to predict places because of large load variation, problems with bolted connections and metal corrosion. Such situations are caused by the fact that silos operate in hard conditions of constant influence of various multi-cycle multi-component loads from the stored material, rigs, adverse environmental conditions and possible seismic influence.

When designing new silos, it is necessary to carry out a comprehensive analysis of SSS of the entire structure using various mathematical models that take into account the structure features and the most adverse combination of various factors. It has been shown in [1, 2] that this is essentially a non-trivial problem requiring additional studies in many fields of science. It is necessary to create new algorithms and approaches to numerical simulation, experimental laboratory studies and testing of actual silos. This task can be partially facilitated by the use of design codes and branch standards [3] which, however, do not completely cover all possible load variations arising in the structure. As a result, a too "soft" estimate of loads [1, 2] is obtained. It follows that development, substantiation and implementation of a complex parametrized mathematical model of SSS of silos and individual elements should be considered the most important and primary task. Only on this basis, it is possible to conduct adequate, accurate and complete numerical simulation of processes in and states of silo elements in the process of construction and operation and, consequently, preparation of appropriate recommendations.

As usual, main structural elements of silos include corrugated panels which are connected with overlapping and corresponding stiffening ribs by means of preliminary tightened bolted connections. Therefore, when constructing an adequate design model, the system of strips (or shells) reinforced by various structural elements is ultimately obtained. The bolt pre-tightening forces act between these elements. Also, forces of contact interaction of the bolt head and the nut with the strip and the cylindrical bolt section with internal surface of the bolt holes bored in the connected strips act in the bolted connections. Such problem formulation takes into account geometric, structural and physical nonlinearity of the structure.

Thus, analysis of the structure and loading conditions shows that the potential significant factors to be taken into consideration during development of the mathematical model and its numerical implementation by means of the finite element method (FEM) include the following:

1) correct application of boundary conditions;

2) detailed analysis of bolted connections in the structure;

3) taking into account friction in "nut-strip-washer-bolt head" combinations;

4) taking into consideration the "slider" effect, that is, modeling tangential displacements of panels under applied normal load;

5) taking into consideration heterogeneity of gap distribution in the "internal strip-bolt-outer strip" system among individual locations of bolted connections;

6) taking into consideration unevenness (variation) of forces in bolted connections.

These peculiarities in formulation of the study tasks are in a good agreement with the problematic moments reflected in [1].

Attention was paid in [4, 5] to numerical and experimental studies of samples of panels connected by bolt fixtures with preliminary tightening. Sandwiches of strips of various thicknesses with various schemes of sandwich formation were studied. Various properties of materials of bolts and connected strips were also taken into consideration. Stages of elastic deformation of the studied structure, slippage as a result of overcoming static friction forces by tensile forces as well as plastic deformation were considered. The obtained results formed the basis for conclusions on characteristic features of behavior of the studied "plates-bolts-plates" nonlinear system. In the long run, it is possible to construct on this basis "phenomenological" models of special finite elements (SFE) embedded in traditional finite element models in the zones of connection of individual silo panels. Such an approach is quite productive and of considerable interest. However, it has certain disadvantages. First, tensioning with longitudinal forces is mainly considered in the study of the specimens described in [4, 5] whereas in reality, the silo elements work in conditions of longitudinal and transverse bending (Fig. 1).

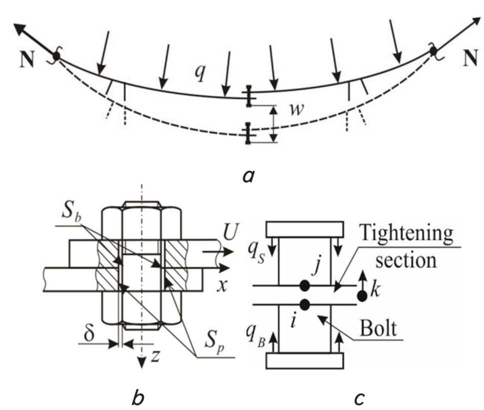


Fig. 1. Diagram of loading of a silo element: diagram of strip connection (*a*); connection diagram and gaps in the bolted connection (*b*); model of bolted connection (*c*)

Under these conditions, the following factors are at the forefront:

1) magnitude of the tensile force, *k*, in the bolt varies during loading (in contrast to practically constant magnitude for the case of longitudinal tension [4, 5]);

2) magnitude of the tensile force in strips, N, has a significant effect on deflection, w;

3) large deflections, w, cause noticeable tangential deformation, and, therefore, affect the force N;

4) there may be a gap between the bolt and the strips (surfaces S_b, S_p) with contacting conditions:

$$(\vec{U}\cdot\vec{V})\Big/S_p+(\vec{U}\cdot\vec{V})\Big/S_b\leq\delta;$$

5) in addition, a plastic gasket having a non-linear pattern of "ε–σ» dependence may be placed between the bolt and the strip surface;

6) contact, friction and slip between of the bolt and the strip surfaces appear.

Combination of factors 1) to 6) reduces the problem to a system of related nonlinear equations that connect together physical, geometric and structural nonlinearities. At the same time, it is impossible to identify dominant factors. Accordingly, the task is considerably complicated in comparison with the cases described in [4, 7].

Given the fact that the analyzed references extensively study SSS of thin-walled structures including those with bolted connections, a problem of substantiation of design models being used arises. In this case, it is possible to isolate individual lines of study. For example, reaction to loading of structures which consist of corrugated panels is studied in [4, 7]. Study of thin-walled structures with bolted connections is described in [6–12]. At the same time, the loading patterns used in these works do not fully correspond to actual conditions of work of these structures. Elastic and elastoplastic behavior of thin-walled structures under seismic loads [13–16], in collapse analysis [12, 17], in determining response of these structures to action of wind loads is not enough adequately modeled [18].

As a rule, only one or several factors are taken into consideration in [1–18] when constructing design models of structures that are being studied. However, as noted in [19–22], it is necessary to take into consideration as wide range of factors as possible in such cases. In particular, an attempt was made in [19] to consider effects of friction force, contact, gaps and geometric nonlinearity on behavior of a composite thin-walled structure with bolted connections but only few structure variants were considered.

Thus, it can be concluded that there is no complete solution to the problems of study of composite thin-walled structures. This necessitates improvement of existing models of SSS and methods for studying behavior of such structures under loading.

3. The aim and objectives of the study

The study objective was to analyze behavior of composite thin-walled structures on the example of two strips with bolted connections.

To achieve this objective, the following tasks were solved:

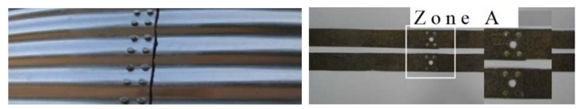
– to formulate problem and construct design diagrams of the test compound system of strips with bolted connections;

– to carry out numerical study of SSS of the composite test strip and analyze the results obtained from the point of view of influence of design parameters on the strip strength.

4. Problem formulation and design diagrams

To study qualitative features of behavior of the "panels-bolts-panels" system (Fig. 2), simplified (test) specimens were studied. The specimens form a system of two strips connected by one or more bolts and loaded with transverse forces. All elements characteristic to silos were present in this test system (TS) and all of the above important factors were taken into consideration (besides corrugations). The TS dimensions are close to dimensions of the strip taken from the metal granary.

It is necessary to develop a mathematical model of the TS SSS using the method of finite elements. Next, it is necessary to study the TS SSS for bending taking into consideration moderate deflections and the effect of longitudinal forces.



a *b*

Fig. 2. The studied system of strips: actual silo structure (*a*); section taken from of the composite strip (*b*)

The test system is modeled as a composite strip: two strips connected by bolt fixtures with a gap (Fig. 3). To be more specific, the following dimensions and material properties were taken in numerical formulation by FEM: module of elasticity of the material E=2.1·10^{11} N/m^2; Poisson coefficient v=0.3; length l=5·10^{-1} m; width C=5·10^{-2} m; thickness h=2·10^{-3} m; the total length of the connected strips L= =9.6·10^{-2} m which corresponds to the length of the span between stiffening ribs on the silo. Diameter of bolt holes in strips d_1=1.2·10^{-2} m; bolt diameter D=10^{-2} m.

Bolted connection arrangement was as follows: the bolt is placed in the strip holes with a gap and tightened with a nut to tightening torque T_K. The tensile load that occurs at the points of strip connection is balanced at initial stages of loading by frictional forces in connections resulted from application of bolt tightening force F_{tight} If the force of tensioning the rods along the x axis exceeds frictional forces, the strips will slip until the gap is vanished. At this moment, cylindrical surfaces of the bolt and holes in the contacting strips begin to work. Main attention is paid to variants of bolted connection arrangements, which influence behavior of gap vanishing during bending of the system. The following changes in connection arrangement will be considered in the presented task (Fig. 4–6).

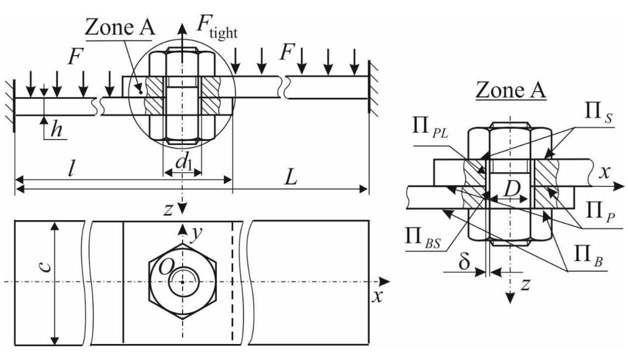


Fig. 3. System of two strips with bolted connection

Design of the bolted connection belonging to the first group is a connection with a single bolt and the use of joint washers made of polypropylene having non-linear elastic properties in the contact areas (Fig. 4). In this task formulation, of coefficients of friction and bolt tightening force were varied and joint washers were used (Table 1). Transverse force distributed on the upper edge of the strips is given by force F (cyclic loading-unloading). The tightening torque is modeled as the force of preliminary bolt tightening F_{tight}. Table 1 shows variants of contact interaction at various bolted connection arrangements.

Table 1

Contact types and coefficient of friction used

Variant No.	F, N	F_{tight}, N	Contact types				
			Friction plate-plate	Friction plate-bolt	Friction-less hole-bolt	Friction plate-washer	Bonded bolt-washer
			Friction coefficient value				
1_1	450	1000	0.2	0.2	+	–	–
1_2			0.2	0.001	+	–	–
1_3			0.0001	0.0001	+	–	–
1_4			0.2	–	+	0.2	+
1_5			0.2	–	+	0.001	+
1_6			0.2	–	+	0.2	+
1_7	450..0	6600	0.2	–	+	0.2	+

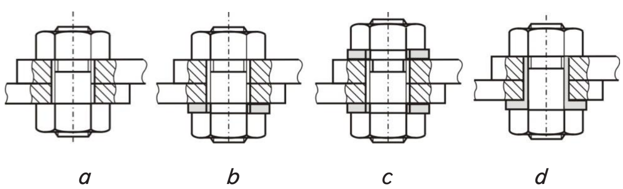


Fig. 4. Group I. Bolted connection arrangement: variable coefficient of friction (bolt-strip, strip-strip, joint washer is absent) (*a*); variable force of tightening the bolted connection, the washer placed between the bolt head and the strip (*b*); use of a joint washer at both sides (*c*); change of the force acting on the upper surface of the strip system (static, cyclic, washer fills the gap)

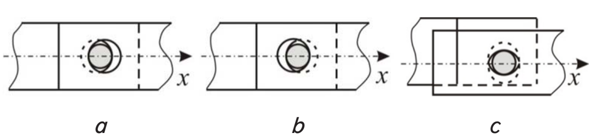


Fig. 5. Group II. Change of concentric position of holes with respect to one another: gap increase (*a*); gap reduction (*b*); side displacement (*c*)

The bolted connection arrangement belonging to the second group (Fig. 5) different hole diameters (Table 2). Also, position and arrangement of the strips relative to the hole axis vary. This misalignment can occur in thin-walled structures during their connection. In the presented task, it is proposed to consider three variants of misalignment (respectively, variants 2_1p–2_3p): displacement of strips with a selected gap between the hole and the bolt (1), increased gap (2) and side displacement of the strips relative to the hole (3).

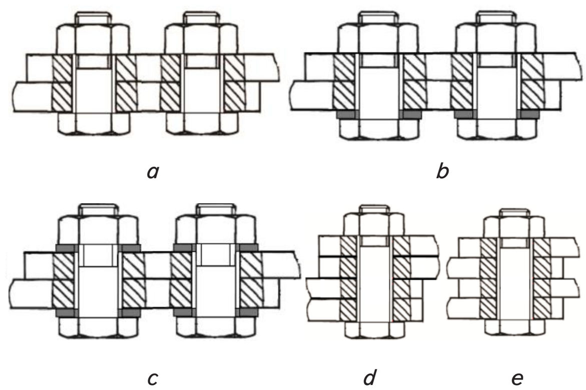


Fig. 6. Group III. Arrangement of bolted connections: two bolted connections without washers (*a*); two bolted connections with two washers (*b*); two bolted connections with four washers (*c*); one bolted connection with two paired strips (*d*); one bolted connection with two alternately connected strips (*e*)

In this formulation, a bolted connection is used with a 0.01 m diameter bolt. When the hole diameter is changed, the gap between the bolt and the inner surface of the hole gets smaller/larger. Because of this, the gap change is accompanied by a decrease or increase in the composite rod bending during loading. This variation makes it possible to analyze the effect of the gap size on SSS of the model of the composite strip under study.

Table 2

The studied list of the bolted connection arrangements

Variant No.	Hole dia., m	F, N	F_{tight}, N	Contact type		
				Friction strip-strip	Friction plate-bolt	Frictionless hole-bolt
				Friction coefficient value		
2_1	0.0102	450	1000	0.2	0.2	+
2_2	0.011					
2_3	0.012					
2_4	0.013					
2_1p	0.012	450	1000	0.2	0.2	+
2_2p						
2_3p						

Elements with an increased number of bolted connections and addition of strips to the studied system are considered in the third group (Fig. 6). Such alternation takes place in thin-walled machine-building structures. Thin-walled panels are interconnected with a different number of bolted connections in a row. Also, composite thin-walled panels are used. They can be single-layered and multilayered. Single-layered panels are two butted panels and multilayered ones are four or more panels in one connection. Multilayered panels are arranged in two ways: two or more panels in a sandwich (1) and successive panel alternation (2). Also, panels are arranged using various number of bolt fixtures. In particular, connection with two bolt fixtures was considered in this task. Joint washers made of physically non-linear materials are used in the described connections. A list of the studied arrangements of strips with various numbers of bolted connections is given in Table 3.

Table 3

The studied arrangements of bolted connections

Variant No.	Strip arrangement	F, N	F_{tight}, N	Contact type: Friction plate-plate	Contact type: Friction plate-bolt	Contact type: Frictionless hole-bolt
				Friction coefficient value		
3_1	Two strips, two bolts	850	1000	0.2	0.2	+
3_2	Two strips, two bolts, two washers	850	1000	0.2	0.2	+
3_3					0.001	
3_4	Two strips, two bolts, four washers	850	1000	0.2	0.2	+
3_1p	Four strips, one bolt (group connection)	1200	1000	0.2	0.2	+
3_2p	Four strips, one bolt (connection with alternation)	1200	1000	0.2	0.2	+

The finite element model. The studied problem is reduced to analysis of the finite element model shown in Fig. 7, 8. 'Sweep' method of finite-element grid was used. The number of elements of SOLID 186 (ANSYS) type in models is from 44 to 90 thousand, the number of nodes from 215 to 435 thousand. Geometric, physical and structural nonlinearities are taken into consideration.

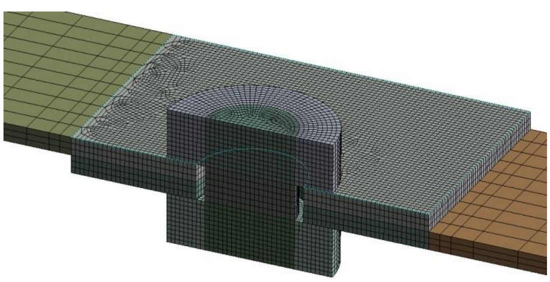


Fig. 7. Finite element model

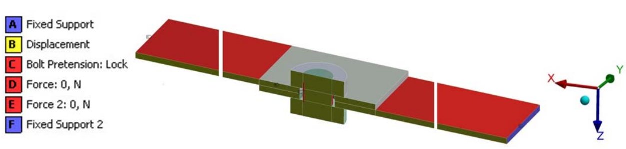


Fig. 8. The test system loading diagram

The model loading diagram is shown in Fig. 8. The structure is considered in a section (symmetric with respect to the xOz plane). Pressure q with a total force F=450 N (Fig. 1, 3) acts on the upper part of the strip. Strips are rigidly fixed at their ends. Movement along y axis in the plane of symmetry xz (Fig. 3) is restricted. The transverse force distributed on the upper edge of the strips is set by the force F (the system is loaded in steps. Preliminary tightening takes place at the first stage. The system is loaded by increments of pressure q, and, accordingly, the force F) at the further stages.

5. Results obtained in numerical simulation of SSS of the test strip with bolted connections

Let us consider the results obtained for *the first group* (I), Fig. 4. They include pictures of system deflections, distribution of equivalent Mises stresses, reactions in the supports, the forces arising in the bolt under loading (Fig. 9, 10).

Analysis of the presented dependences provides the basis for the following conclusions:

1. Deflections of the system of strips (Fig. 9, *a*) is a step function. Plain sections correspond to deflection of the strip as a solid rod (in this case, the friction force is less than the limit value and mutual slip of the strip does not occur). When the friction force becomes equal to the limit value, a sharp increase in deflections takes place. This increase is caused by "extension" of the strip because of mutual slipping of its halves. "Plain" and "sharp" stages alternate until the gap between the bolts and panels vanishes. Further growth of the load leads to a slow growth of deflections without sharp jumps. In this case, the system of these strips behaves as a continuous strip (CS) but is lengthened by the size of the gap between the bolt and holes in the strips.

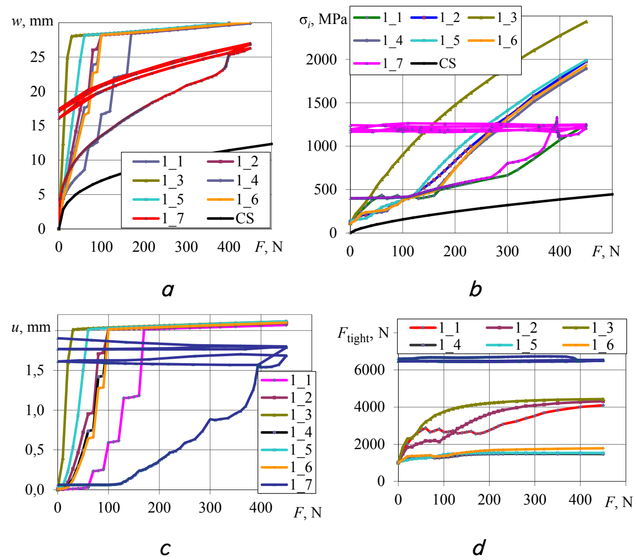


Fig. 9. The results of numerical simulation of the first group for all variants of connections under action of load F, N: deflection w, mm (a); maximum equivalent Mises stresses σ_i, MPa (*b*); displacement of the contact surfaces relative each other и, mm (mutual slip) (*c*); force in the bolt F_{tight}, N (*d*)

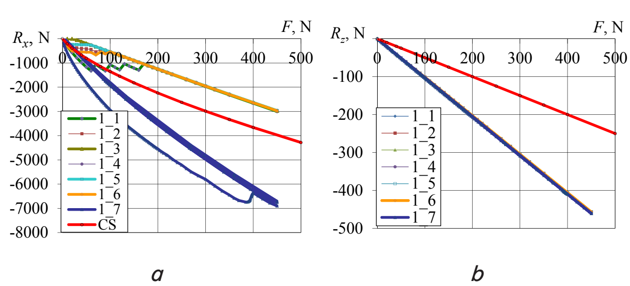


Fig. 10. Reaction in fixtures for all variants of connections depending on external load F, N: along x axis R_x, N (*a*); along z axis R_z, N (*b*)

2. When the coefficient of friction decreases, stepwise behavior changes to plain curvilinear and a displacement of strips relative to each other occurs at a smaller load.

3. The use of a joint washer that fills the gap leads to a plainer vanishing of the gap. The load that is required for displacement of strips increases.

4. Under the action of a cyclic load, two zones are observed: the first zone is growth of deflections with increasing load. At the same time, regions of "sharp" and "plain" change of deflections are realized alternately. The second zone is a weak gradual growth of deflections with a further increase in load and a reverse change occurs with a decrease in load to zero (a case is considered without change of the load sign). A significant residual deflection remains in the studied system after the "loading-unloading" cycle (in this case, at a level of 60 % of the maximum). Further "loading-unloading" cycles occur practically by the same path as in the initial cycle. Thus, it can be noted that when load is taken off, the system does not return to its original state. With a further pulsating cyclic loading (from zero to maximum and then back to zero), the system behaves like a "pseudo-elastic" but with some residual deflection.

5. The levels and distributions of equivalent Mises stresses are shown in Fig. 9, *b*, 11, 12. Fig. 12 illustrates comparison of emerging maximum stresses in all arrangements of bolt fixtures (Table 1). These stresses nonlinearly grow with the load increase. If there is sealing material in the gap of the bolted connection, it levels the stress concentration.

6. To analyze displacements of the contacting surfaces of the strips, consider dependence of displacements of strips relative to each other along the x axis under load (Fig. 9, *c*). A stepwise behavior of strip displacements with growth of loading is observed. No displacements occur at the initial load. With an increase in load up to 50 N, a jump-like displacement of strips appears relative to each other which is accompanied by a partial gap vanishing. With a further growth of the load (after a complete vanishing of the gap), a slight displacement is observed only as a result of deformation of the contacting strips and bolts.

7. Let us consider also reactions in places of plate fixation (Fig. 10). It should be noted that longitudinal reaction components, in contrast to the transverse ones, vary almost nonlinearly. However, with growth of the load after onset of contact of the bolt with edges of the holes, the reaction components grow approximately linearly. It is important to note that the level of longitudinal reactions remains practically constant when strips are displaced. Besides, the level of longitudinal loading is an order of magnitude higher than that of transverse loading (and, accordingly, the reactive force along the z axis, Fig. 3). It should also be noted that in other variants (Tables 2, 3), dependence of reactions R_x and R_z on transverse loading is similar (and, therefore, they are not discussed further).

8. A significant effect of sharp increase in tensile force in the bolt is possible. In some cases, this force may exceed the level of initial tightening more than 4 times (Fig. 9, *d*). To reduce this effect, it is suggested to use joint washers. In particular, the studied arrangement of the bolted connection in the contact between the strips and the bolt head through two yielding washers (variant 1_4) has made it possible to understand causes of force increase in the bolt. Reaction will increase when the parts are rigidly connected. When introducing yielding elements into the system, no marked increase in tightening forces occurs in comparison with the initial value. When there is an increase in the tightening force of the bolt fixture with the washer that fills the gap (variant 1_7), reaction in the bolt remains virtually unchanged.

Let us consider the results obtained for *the second group* (II, Fig. 5). Fig. 13 shows results of the study with varying hole diameter (Table 2). Based on the obtained results, the following tendency is observed. With an increase in hole diameter, the value of deflection increases nonlinearly: about 0.035 m at diameter of 0.013 m and about 0.017 m at diameter of 0.0102 m. With increase in hole diameter, equivalent Mises stresses and forces in the bolt begin to increase significantly with complete vanishing of the gap when the bolt gets into contact with the surface of the hole.

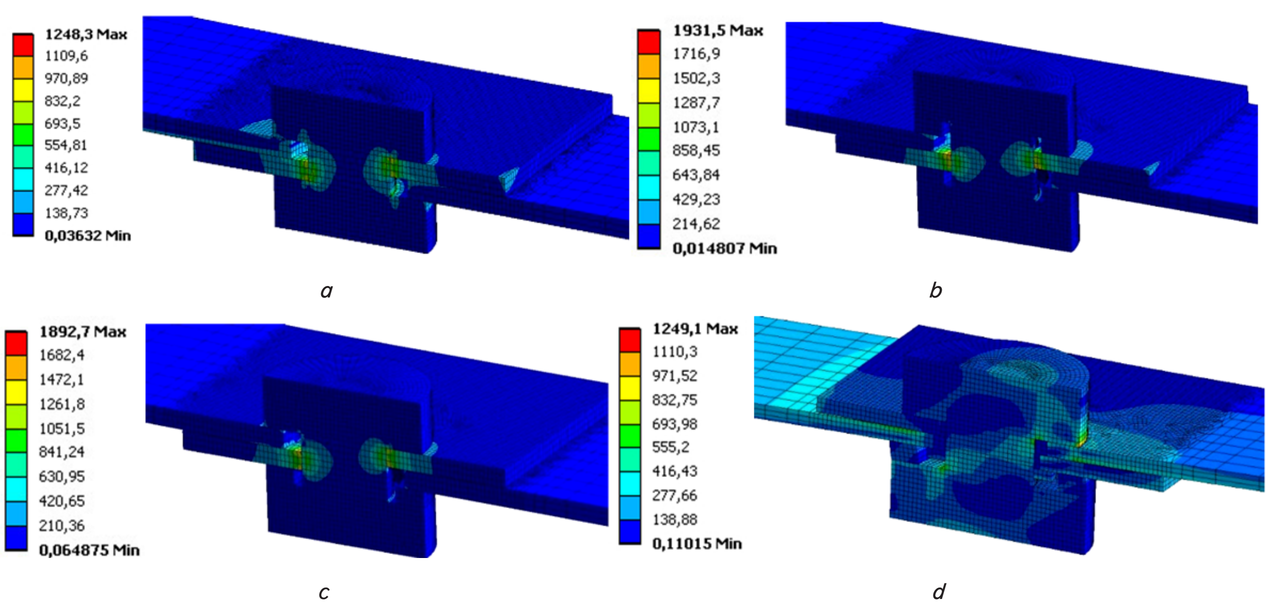


Fig. 11. Distribution of equivalent Mises stresses: variant 1_1 (*a*); variant 1_4 (*b*); variant 1_6 (*c*); variant 1_7 (*d*)

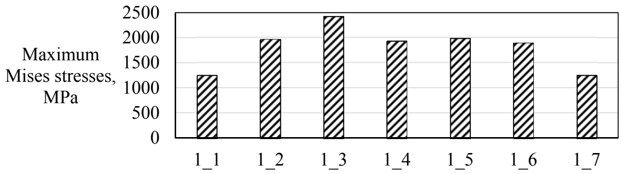


Fig. 12. Maximum equivalent Mises stresses (MPa) for variants 1_1–1_7 (Table 1)

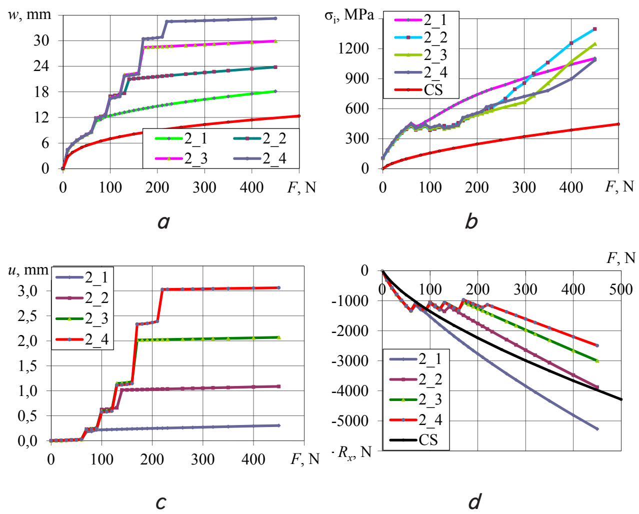


Fig. 13. Results of numerical simulation of the second group for all connection variants: deflection *w*, mm (*a*); maximum equivalent Mises stresses σ_i, MPa (*b*); displacement of contacting surfaces of the strips relative yo each other *u*, mm (mutual slipping) (*c*); reaction in the fixture along *x* axis R_x, N

When comparing the studied system of strips in a geometrically nonlinear formulation with a conventional formulation for a continuous strip (CS), one can state the following. There is a significant difference between deflections, equivalent stresses and reaction components in supports. Behavior of the continuous strip is shown in graphs as more smooth and linear while behavior of nonlinear character is manifested substantially in the system of interconnected strips studied and described above. When a continuous strip is loaded, the value of deflection is more than twice less than that of deflection in the system of strips with bolt fixturing depending on the hole diameter. This is explained by the fact that there is a structural nonlinearity in the system of strips with bolt fixturing, and there are significant gaps (depending on diameter) in holes commensurate with the values of displacement of points in the strips as a result of elastic deformations. Thus, conventional formulation of such a class of problems with a design diagram in the form of a continuous strip without taking into consideration bolt fixturing, gaps, tension and friction results in a significant inaccuracy in the results obtained.

When strips are laterally displaced relative to the holes, an additional influence on the deflection behavior takes place (Fig. 14, *a*). When strips with an increased gap are displaced, the deflection is about 0.04 m. When the gap is reduced, deflection equals to 0.018 m. It is equal to 0.025 m when strips are displaced laterally. Behavior of deflection becomes stepped and nonlinear with loading growth. Maximum stresses were observed in the first and third variants after gap vanishing (Fig. 14, *b*). In the second variant, stress growth occurs immediately at the beginning of loading. Behavior of slippage of strips relative to each other corresponds to the change of deflection (Fig. 14, *c*). Force in the bolt increases during the system loading. Nonlinear increase to 3500 N is observed in the first variant and about 4000 N in the second variant. The force is maximal and equals to about 6000 N (Fig. 14, *d*) in the third variant when lateral displacement takes place.

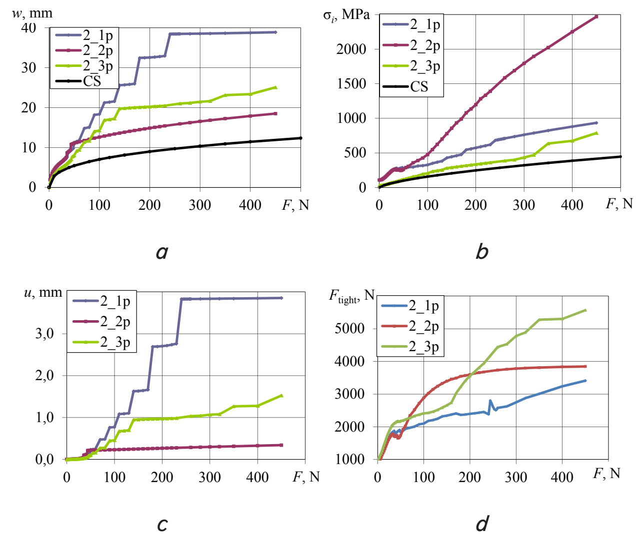


Fig. 14. Results of numerical simulation of the second group at various strip displacements: deflections *w*, mm (*a*); maximum equivalent Mises stresses, MPa (*b*); displacement of contacting surfaces of strips relative to each other *u*, mm (mutual slipping); forces in the bolt under action of loading F_{tight}, N

The results of study of the *third group* (III, Fig. 6). Let us consider the results of study of the system of strips with two bolted connections (Fig. 15). It follows from the results that application of two bolted connections in the studied system of strips leads to an increase in the force required for gap vanishing (compared to the system with one bolted connection). It is about 400 N in the bolted connections without joint washers and about 250 N in the bolted connections with joint washers. Gap vanishing occurs gradually along with nonlinear behavior of deflection. Deflection was about 0.027 m in all variants (Fig. 15, *a*). Equivalent Mises stresses were 1,126 MPa in the first variant, 1,844 to 2,083 MPa in the second variant depending on the coefficient of friction and 1,876 MPa in the third variant with two joint washers (Fig. 15, *b*, 16). Forces in bolted connections begin to grow significantly when the gap vanishes. Reaction in the bolts grows from 1,000 N to 4,000 N in a connection without joint washers, up to 1,700 N in the variant with two washers and up to 1,300 N in the variant with four washers. It follows from these results that the use of joint washers significantly affects performance of the bolted connections.

Let us consider the results obtained for *multi-layered panels with group arrangement* (variant IV) (Fig. 6) and *arrangement by the method of sequential alternation* (variant V) (Fig. 16–18). Graphs of dependence of the system deflections under loading having maximum value about 0.030 m are shown in Fig. 17. Maximum equivalent Mises stresses in variants IV and V are approximately equal to 2,200 MPa

(Fig. 17, *b*). Displacement of the strips (Fig. 17, *c*) and bolt forces (Fig. 17, *d*) have the same nature of dependence on the load *F* as in the previous variants.

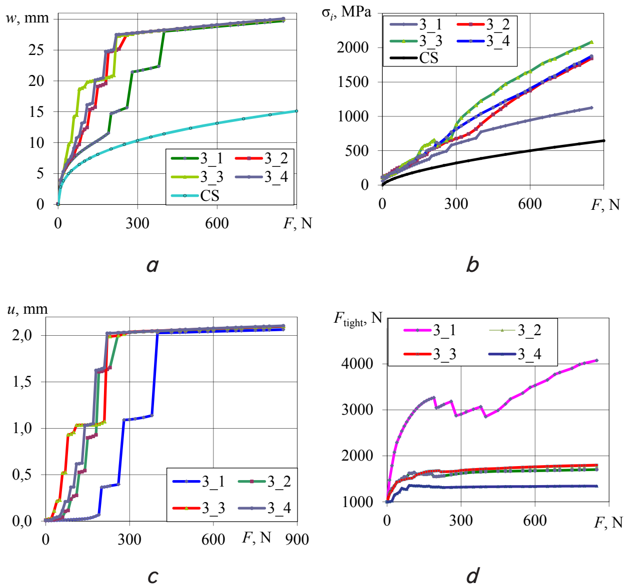


Fig. 15. Results of numerical simulation of the third group for all variants of connections under the action of loading *F*, N: deflection *w*, mm (*a*); maximum equivalent Mises stresses σ_i, MPa (*b*); displacement of contacting surfaces of the strips relative to each other *u*, mm (mutual slipping) (*c*); force in the bolt F_{tight}, N

Models at the moments of gap vanishing along with maximum equivalent Mises stresses arising in the contacts between bolts and strips are illustrated in Fig. 18. There is a difference between these two variants for the entirely vanished gap. The gap completely vanishes at 200 N in the first variant and at 600 N in the second variant.

Having analyzed the obtained results, the following conclusions can be drawn: behavior of deflections of the system of strips depends on arrangement of thin-walled elements (group connection and alternation method). In the first variant of arrangement, the gap vanishes at a load level lower than in the second variant. This is explained by the fact that the number of contacting surfaces with friction is equal to three in the first variant and five in the second variant. Stresses by Mises are in the same range.

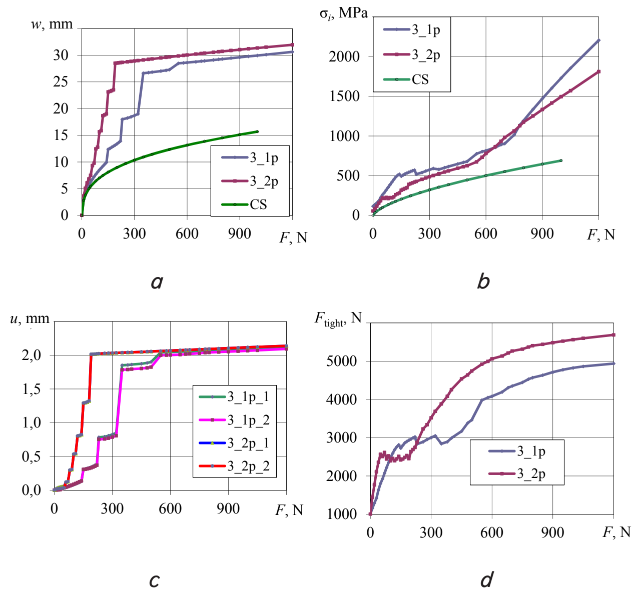


Fig. 17. The results of numerical simulation of the fifth group at different displacement of strips under the influence of load *F*, N: deflection *w*, mm (*a*); maximum equivalent Mises stresses σ_i, MPa (*b*); displacement of contacting surfaces of the strips relative to each other *u*, mm (mutual slipping) (*c*); forces in the bolt F_{tight}, N

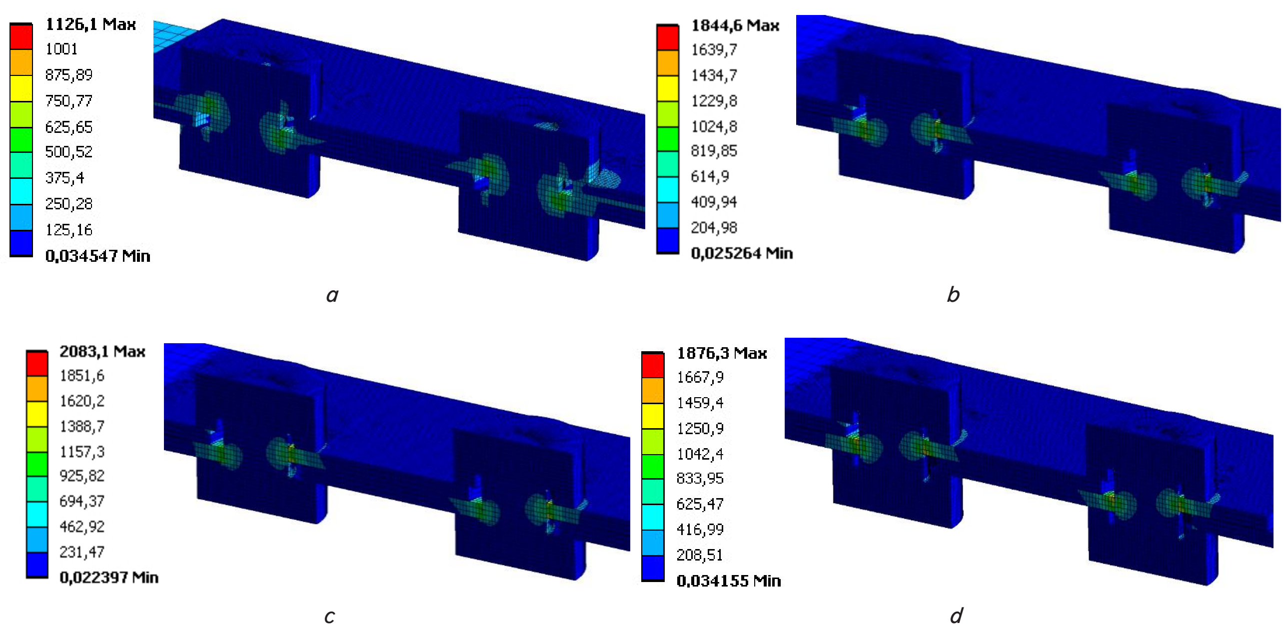


Fig. 16. Maximum equivalent Mises stresses (Fig. 6, *c*): variant 3_1 (*a*); variant 3_2 (*b*); variant 3_3 (*c*); variant 3_4 (*d*)

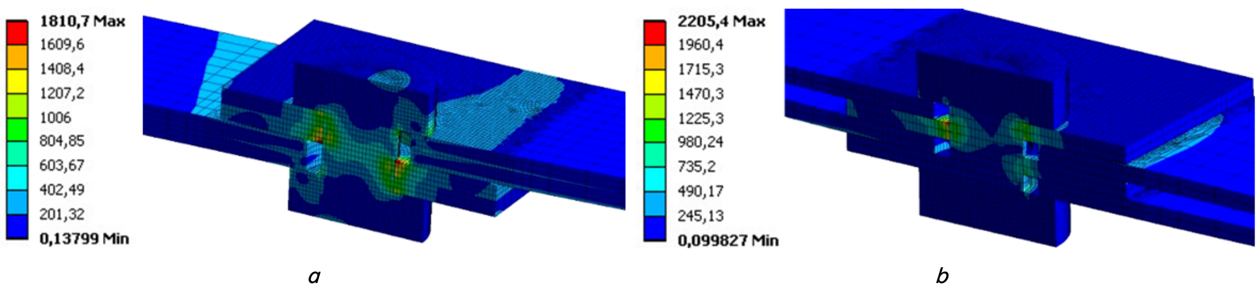


Fig. 18. Distribution of equivalent Mises stresses (Table 3): variant 3_1p (*a*); variant 3_2p (*b*)

6. Discussion of results obtained in the study of SSS of a thin-walled structure with bolted connections

The described study is a continuation and development of studies [19–22].

It should be noted that the models developed and described in this paper have significant advantages over conventional ones. First, they take into consideration additional factors that were insufficiently taken into consideration in earlier studies (contact, friction, slip, variable force in the bolted connections). Secondly, all these factors act in interaction and interconnection. Thirdly, the created model more adequately reflects physical essence of the processes and states realized in the studied structures.

It should also be noted that application of developed models has established new patterns of behavior of thin-walled structures with bolted connections. In particular, the effects of reaction of such structures to the effect of loading were established. This reaction combines stages of elastic deformation and mutual slipping of the strips. Residual deformation is accumulated in the composite strip at the first loading. It is determined by gap vanishing. After the first loading, the system is mainly deformed in an elastic region.

The constructed models and revealed features of behavior of thin-walled structures with bolted connections can be used in structure studies of silos of various sizes, shapes and purposes. The developed models give fundamentally more accurate results (compared to conventional ones). For example, in the failure to consider deformation of the bolted connection, deflections of the composite strip are 2–3 times smaller than when taking into consideration this factor.

However, it should be noted that the constructed models do not take into consideration some factors inherent to actual structures of silos. First of all, it concerns the type of the load which can be multiple-cycle and alternating. Besides, possible loss of stability is not taken into consideration when compression forces occur in the strip. It is also worth investigating the effect of corrugations on behavior of structures of this type.

The noted problem issues are directions to further studies.

7. Conclusions

1. The developed model of designing thin-walled structures with bolted connections has advantages over conventional models. Unlike the simpler models, it takes into consideration geometric, physical and structural nonlinearities. Taking into consideration friction makes it possible to determine dependence of the studied system state on the loading history. The achieved properties give an opportunity to more adequately simulate stress-strain state of thin-walled structures with bolted connections.

2. Design diagrams, coefficients of friction, gaps and loads were varied in numerical studies of SSS of a composite strip with bolted connections. As a result, regularities of their influence on SSS of the studied structure were established.

3. Analysis of the obtained behavioral characteristics of the studied structures has made it possible to state the following:

– regardless of the variant of embodiment, presence or absence of the joint washer as well as the number of bolted connections, deflection of the studied composite strip is similar for different variants of the composite strip by its character of transverse loading, however, it differs sharply from behavior of continuous strips. In particular, there is a combination of plain areas and sharp increments. The first ones correspond to bonding of the strips caused by friction due to bolt tightening. The second accompany slippage of the strips. After a full vanishing of the gap between the bolt side surface and the bolt holes in the strips, the system becomes comparable to a continuous strip but with residual deflections;

– deflection of the studied composite strip responds in different ways to single and cyclic application of transverse load. Two stages are clearly distinguished in a single loading. The first stage combines gradual and sharp changes of deflection. Then (after vanishing of the gap), the stage of only plain growth of deflection comes. If the system is unloaded after this point, it does not return to its original state. Residual deflection is formed. Further cyclical loading and unloading (without changing the load sign) occurs along the curve corresponding to the first unloading. Thus, the system acquires residual deformations mainly in the first loading cycle. Practically nonlinear-elastic deformation of the strip system occurs in subsequent cycles;

– the stressed state of the studied system of strips is characterized by the fact that the Mises stresses are concentrated in the panels in the zone of bolted connections. The maximum values of stresses with the load growth behave nonlinearly. In multiple-cycle loading, accumulation of a certain value of residual stresses at the first stage occurs first and then their nonlinear elastic change occurs. It should be noted that a model problem was considered: it was assumed that the material of the strips works in an elastic region despite the high level of stress;

– an effect of possible sharp increase in tensile forces in the bolt was detected during loading of the studied system of strips. This is especially evident in the absence of a joint washer. Therefore, application of a model with a fixed force in the bolted connections is inadmissible in a general case;

– control over behavior of longitudinal forces in the studied system has made it possible to establish that when load increases, they sharply increase from zero to values exceeding transverse load several times. This indicates that deflections cause significant extension of the studied strip and the longitudinal forces resulting from this, in turn, affect deflection. It turns out that mutual influence of stretching and bending takes place. Thus, like in the case of continuous strip, it is necessary to determine SSS from stretching and bending together. However, unlike the case of a continuous strip, composite strip demonstrates an additional elongation and deflection not only due to elastic deformations but also due to the possible mutual slip of the strips relative to each other. This results in a more complicated connection between stretching, sliding and bending. This feature must be taken into consideration in the design models of such structures;

– an increase in the number of bolted connections leads to a noticeable "strengthening" of the structure. The structure is also "strengthened" by the use of multilayered strips which are stacked by superimposing strips to the left and to the right alternately;

– introduction of a joint plastic washer between the bolt head and the strip, between the nut (metal washer) and the strip, between the side of the bolt and the hole in the strip "smoothes" but not eliminates the revealed features of behavior of the studied composite strip.

4. The established features and regularities of SSS of a composite strip with bolted connections show that consideration of the contact, friction and slip, forces of bolt tightening and deformation of a yielding washer-spacer dramatically change behavior of the test system compared with the continuous strip. Accordingly, these factors need to be taken into consideration in the design models of such systems.

References

1. Ayuga F. Some unresolved problems in the design of steel cylindrical silos // Structures and Granular Solids. 2008. P. 123–133. doi: https://doi.org/10.1201/9780203884447.ch12
2. Carson J., Craig D. Silo Design Codes: Their Limits and Inconsistencies // Procedia Engineering. 2015. Vol. 102. P. 647–656. doi: https://doi.org/10.1016/j.proeng.2015.01.157
3. Eurocode 3. Design of steel structures. Silos. BSI, 2007. 122 p. doi: https://doi.org/10.3403/30047480u
4. Tang G., Yin L., Guo X., Cui J. Finite element analysis and experimental research on mechanical performance of bolt connections of corrugated steel plates // International Journal of Steel Structures. 2015. Vol. 15, Issue 1. P. 193–204. doi: https://doi.org/10.1007/s13296-015-3014-4
5. Shi Y., Wang M., Wang Y. Analysis on shear behavior of high-strength bolts connection // International Journal of Steel Structures. 2011. Vol. 11, Issue 2. P. 203–213. doi: https://doi.org/10.1007/s13296-011-2008-0
6. A simplified analytical procedure for assessing the worst patch load location on circular steel silos with corrugated walls / Gallego E., González-Montellano C., Ramírez A., Ayuga F. // Engineering Structures. 2011. Vol. 33, Issue 6. P. 1940–1954. doi: https://doi.org/10.1016/j.engstruct.2011.02.032
7. Mohammed H., Kennedy J. B. Fatigue Resistance of Corrugated Steel Sheets Bolted Lap Joints under Flexture // Practice Periodical on Structural Design and Construction. 2009. Vol. 14, Issue 4. P. 242–245. doi: https://doi.org/10.1061/(asce)sc.1943-5576.0000021
8. Elastic behaviour of bolted connection between cylindrical steel structure and concrete foundation / Hoang V.-L., Jaspart J.-P., Tran X.-H., Demonceau J.-F. // Journal of Constructional Steel Research. 2015. Vol. 115. P. 131–147. doi: https://doi.org/10.1016/j.jcsr.2015.08.024
9. Load-bearing capacity of occlusive high-strength bolt connections / Guo X., Zhang Y., Xiong Z., Xiang Y. // Journal of Constructional Steel Research. 2016. Vol. 127. P. 1–14. doi: https://doi.org/10.1016/j.jcsr.2016.07.015
10. Behavior of single bolt bearing on high strength steel plate / Wang Y.-B., Lyu Y.-F., Li G.-Q., Liew J. Y. R. // Journal of Constructional Steel Research. 2017. Vol. 137. P. 19–30. doi: https://doi.org/10.1016/j.jcsr.2017.06.001
11. Experimental and numerical study of frictional effects on block shear fracture of steel gusset plates with bolted connections / Zeynali Y., Samimi M. J., Mazroei A., Marnani J. A., Rohanimanesh M. S. // Thin-Walled Structures. 2017. Vol. 121. P. 8–24. doi: https://doi.org/10.1016/j.tws.2017.09.012
12. Structural performance of double-wall steel insulation silo with multiple bolted joints / Tang G., Yin L., Li Z., Pan C., Lai H. // Journal of Constructional Steel Research. 2017. Vol. 139. P. 411–423. doi: https://doi.org/10.1016/j.jcsr.2017.09.020
13. Hu F., Shi G., Shi Y. Constitutive model for full-range elasto-plastic behavior of structural steels with yield plateau: Formulation and implementation // Engineering Structures. 2018. Vol. 171. P. 1059–1070. doi: https://doi.org/10.1016/j.engstruct.2016.02.037
14. Shi G., Hu F., Shi Y. Comparison of seismic design for steel moment frames in Europe, the United States, Japan and China // Journal of Constructional Steel Research. 2016. Vol. 127. P. 41–53. doi: https://doi.org/10.1016/j.jcsr.2016.07.009
15. Kanyilmaz A., Castiglioni C. A. Reducing the seismic vulnerability of existing elevated silos by means of base isolation devices // Engineering Structures. 2017. Vol. 143. P. 477–497. doi: https://doi.org/10.1016/j.engstruct.2017.04.032
16. Tu P., Vimonsatit V. Silo quaking of iron ore train load out bin – A time-varying mass structural dynamic problem // Advanced Powder Technology. 2017. Vol. 28, Issue 11. P. 3014–3025. doi: https://doi.org/10.1016/j.apt.2017.09.012
17. Ozolins O., Kalnins K. An Experimental Buckling Study of Column-supported Cylinder // Procedia Engineering. 2017. Vol. 172. P. 823–830. doi: https://doi.org/10.1016/j.proeng.2017.02.130
18. Failure analysis of steel silos subject to wind load / Raeesi A., Ghaednia H., Zohrehheydariha J., Das S. // Engineering Failure Analysis. 2017. Vol. 79. P. 749–761. doi: https://doi.org/10.1016/j.engfailanal.2017.04.031

19. A numerical analysis of non-linear contact tasks for the system of plates with a bolted connection and a clearance in the fixture / Atroshenko O., Bondarenko O., Ustinenko O., Tkachuk M., Diomina N. // Eastern-European Journal of Enterprise Technologies. 2016. Vol. 1, Issue 7 (79). P. 24–29. doi: https://doi.org/10.15587/1729-4061.2016.60087
20. Thinwalled structures: analysis of the stressedstrained state and parameter validation / Tkachuk M., Bondarenko M., Grabovskiy A., Sheychenko R., Graborov R., Posohov V. et. al. // Eastern-European Journal of Enterprise Technologies. 2018. Vol. 1, Issue 7 (91). P. 18–29. doi: https://doi.org/10.15587/1729-4061.2018.120547
21. Numerical methods for contact analysis of complex-shaped bodies with account for non-linear interface layers / Tkachuk M. M., Skripchenko N., Tkachuk M. A., Grabovskiy A. // Eastern-European Journal of Enterprise Technologies. 2018. Vol. 5, Issue 7 (95). P. 22–31. doi: https://doi.org/10.15587/1729-4061.2018.143193
22. Tkachuk M. A numerical method for axisymmetric adhesive contact based on kalker's variational principle // Eastern-European Journal of Enterprise Technologies. 2018. Vol. 3, Issue 7 (93). P. 34–41. doi: https://doi.org/10.15587/1729-4061.2018.132076

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MODELING THE ELASTIC IMPACT OF A BODY WITH A SPECIAL POINT AT ITS SURFACE

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Розглянуто пружний прямий удар по плоскій границі нерухомого півпростору тіла, обмеженого в зоні контактної взаємодії поверхнею обертання, порядок якої менший двох. Особливість задачі полягає в тому, що для вибраного випадку нескінченна кривизна граничної поверхні в точці первісного контакту, з якої розпочинається процес динамічного стискання тіл у часі. Крім основних припущень не хвильової квазистатичної теорії пружного удару твердих тіл, тут використано також відомий розв'язок статичної вісесиметричної контактної задачі теорії пружності. Процес удару з невеликою початковою швидкістю поділено на два етапи, а саме на динамічне стискання і динамічне розтискання. Для кожного з них побудовано аналітичний розв'язок нелінійного диференціального рівняння відносного зближення у часі центрів мас тіл. Розв'язок нелінійної задачі з початковими умовами для диференціального рівняння другого порядку на першому етапі виражено через Ateb-синус, а на другому – через Ateb-косинус. Для спрощення розрахунків складено окремі таблиці вказаних спеціальних функцій, а також запропоновано компактні апроксимації їх елементарними функціями. Встановлено, що похибка аналітичних наближень обох спеціальних функцій менша одного відсотка. Виведено також замкнені вирази для обчислень максимальних значень: стискання тіл, сили удару, радіуса кругової площадки контакту та тиску, який обмежений у центрі цієї площадки. Розглянуто числовий приклад, пов'язаний з ударом жорсткого пружного тіла по гумовому півпростору. Задачі такого типу виникають при моделюванні динамічної дії кусків твердої мінеральної сировини на гуму, при падінні їх на футеровані гумою валки вібраційного класифікатора. Внаслідок порівняння розрахованих параметрів удару, одержано гарну узгодженість числових результатів, до яких призводять побудовані аналітичні розв'язки та інтегрування нелінійного рівняння на комп'ютері. Цим підтверджена вірогідність побудованих аналітичних розв'язків задачі удару, які дають розгортку короткочасного процесу в часі

Ключові слова: пружний удар, особлива точка на поверхні контакту, періодичні Ateb-функції

1. Introduction

The impact interaction between solid bodies typically occurs over a short period of time and is accompanied by large dynamic loads, which could result in the possible destruction of structures' elements. Thus, it is only natural that the simplest theories for calculating the canonical bodies for strength upon impact are highlighted in the resistance of materials [1, 2]. They consider an impact to be instantaneous and, rather than the magnitude of force, apply its momentum. Actually, they consider not the process of a mechanical impact, but its consequences, that is a post-impact motion.