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Research of the specific steel shells progressive collapse prevention

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The article deals with coatings in the form of the specific steel shells. After a detailed analysis certain number of accidents and collapses, these collapses can be classified as “progressive” collapse. The main purpose of the article is the development of design algorithms for evaluation of the stress-strain state and preventing the progressive collapse of the specific steel shells. The method of prevention progressive collapse has been developed in the form of a constructive modernization. The comparative finite-element analysis of the strained-strain state of the specific shells original models, models of discrete-continual ribbed shells (with constructive upgrading) and models of solid ribbed shells has been carried out. From the analysis results it can be concluded that the proposed modernization method can be considered as one of the possible options for preventing progressive collapses and increasing the bearing capacity of specific steel shells.

Keywords: steel shell, arched thin-walled profiles, progressive collapse, buckling, open-type cylindrical compound shell.

Дослідження запобіганню прогресуючого обвалення металевих оболонок спеціального виду

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В статті розглянуті покриття та безкаркасні споруди у вигляді металевих оболонок спеціального виду. Основним конструктивним елементом цих спеціальних оболонок є аркові тонкостінні профілі холодного деформування, які виготовляються безпосередньо на будівельному майданчику. Розглянуті основні аномалії експлуатації зазначеного конструкцій зазначеного виду. Основна з означених аномалій експлуатації полягає у певній кількості аварій та обвалень, які після детального аналізу можна класифікувати як прогресуюче, або «лавиноподібне» обвалення. До основної мети статті відноситься розробка розрахункових алгоритмів оцінки напруженно-деформованного стану та заходів, що попереджують настання прогресуючого обвалення металевих оболонок спеціального виду. Розроблено спосіб запобігання прогресуючого обвалення, у вигляді конструктивної модернізації оригінального вузла з’єднання аркових конструктивних елементів. Проведено порівняльний скінченно-елементний аналіз напруженодеформованого стану, амплітудно-частотних характеристик та стійкості оригінальних моделей металевих оболонок спеціального виду, моделей дискретно-континуальних ребристих оболонок (з імплементацією конструктивної модернізації вузла з’єднання) та моделей континуальних ребристих оболонок. Результати аналізу подано у вигляді мозаїк вертикальних переміщень, головних стискаючих та розтягуючих напружень, порівняльної діаграми коефіцієнтів запасу стійкості та порівняльної діаграми значень частот власних коливань в залежності від номера форми власних коливань. Отримані результати чисельних досліджень, свідчать про ефективність запропонованої конструктивної модернізації металевих оболонок спеціального типу, в якості заходів, що попереджують настання прогресуючого обвалення зазначених оболонкових систем.

Ключові слова: металева оболонка спеціального виду, аркові профілі, прогресуюче обвалення, стійкість

Introduction

The considered coatings are based on arched structural elements that are combined with each other by a folded joint into a folded open-type ribbed cylindrical shell (Figure 1). The construction of structural elements takes place directly at the construction site, in addition, the mobility of the equipment (profile bending equipment) and transport compactness of the original construction material (coiled steel) enables to build objects for various purposes in the shortest possible time.

Figure 1 – The special type steel shell

Despite the frequency of use, the stress-strain state and the stability of the designated special coatings remain poorly considered. Anomalies and collapses that occur during this type of metal special shells operation are of considerable scientific interest.

Review of research sources and publications

These structures are considered in the works of Zverev V. [1] and Zhidkova K. [2] where arched structures are considered on the basis of volume-formed rolled metal. In the calculation of structures where the profiles have corrugated limits, the method based on the replacement of such faces is anisotropic with plates of similar thickness, which is widely used. Characteristics of rigidity which are found from the condition of equality of linear displacements of corrugated and flat anisotropic plates, along the respective coordinate axes, this simple but effective engineering method was proposed in the works of Andreeva L.Ye. [3, 4], where three types of corrugations are considered: trapezoidal, serrated and sinusoidal. In [5], the effect of virtual imperfections on the stress-strain state of the considered arch coverings was evaluated. The article [6] is devoted to defining the features of cold-formed trapezoidal arched profiles cross-sections work of the "IIA" type system as part of the coating shell. In [7], algorithms for calculating special type of arch covers have been added.

Articles [8], [9] provide information on the complexity of operation, a certain number of accidents and their probable causes for shell systems that are considered.

Definition of unsolved aspects of the problem

The most common causes of collapses appearing in expert opinions regarding an accident include:

– project errors;
– technological defects;
– violation of the exploitation rules.

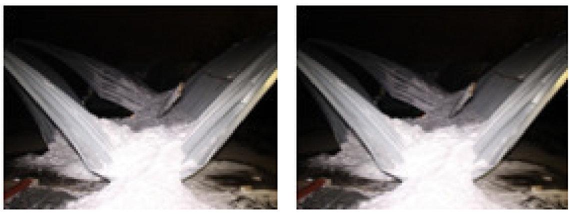
Analyzing the collapse nature and rate, the so-called "progressive" or "avalanche" collapse occurs, in other words, a buckling of the described cylindrical ribbed shells occurred. In Fig. 3 shows a frame-by-frame fixation from a CCTV camera, the process of the arched structure collapse.

Problem statement

The main goal of the article is the development of computational algorithms for assessing the stress-strain state and measures that prevent the onset of the specific steel shells progressive collapse.

2017, The collapse of the granary (Ukraine) 2018, The collapse of the coating (Ukraine)

2014, The collapse of a warehouse (Russia)



2017, The collapse of parking structures (Belarus)

2018, The collapse of the granary (Ukraine) 2016, The collapse of the IceArena (Russia)

Figure 2 – Instances of the anomalies of exploitation of special type shells

Figure 3 – A 60 meter long structure collapsed in less than 10 seconds

Basic material and results

Establishing and ensuring the protection of buildings and structures from possible progressive collapse covers a wide range of approaches considering the nature and effects of various loads. At the same time, general recommendations are to use the simplest calculation methods that meet the requirements of construction, but the non-triviality of metal shell structures are considered, encourages their transformation and the used numerical models improvement.

The improved algorithm (and its verification) of these structures stress-strain state analysis reflect the possibility of progressive collapse, it is considered in the article that is now in-print entitled «Progressive collapse of the special-type arch systems: modeling algorithm» that has been written by the authors P. Reznik, L. Gaponova, S. Grebenchuk, R. Koreniev. A feature of this approach is to display the design nonlinearity of the specific metal shells and to use the potential deformation energy as a criterion for the carrying capacity exhauster 10] with the implementation of information technologies and approaches mentioned in [11]. The algorithm is generally illustrated in Fig. 4.

An example of the short shell model calculation results, with the implementation of the above principles, is shown in Fig. 5.

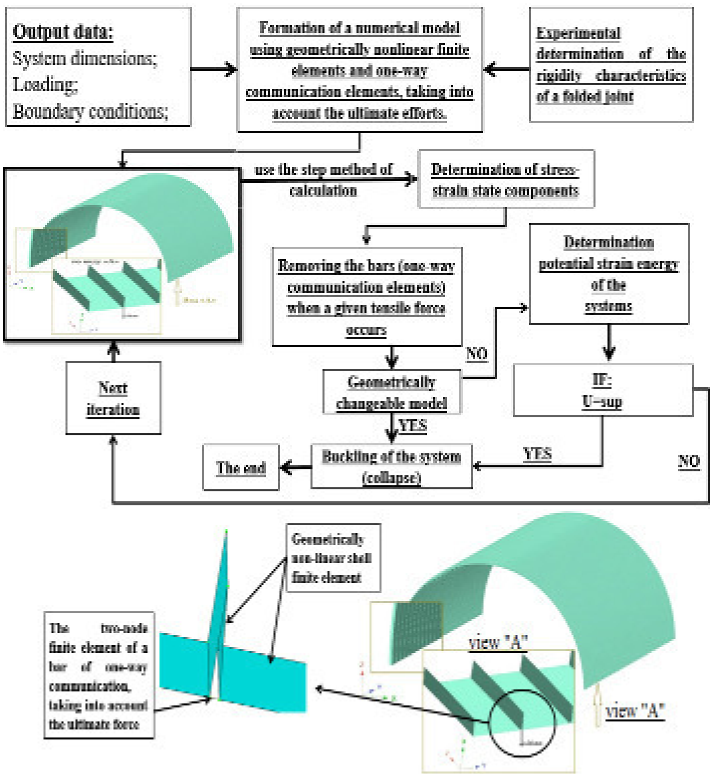


Figure 4 – The flowchart of the research stress-strain state algorithm of the arch-type system, considering the deformed scheme and probability of progressive collapse

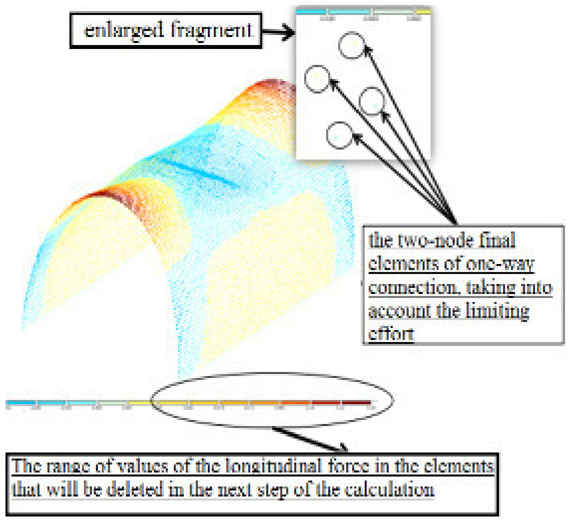


Figure 5 – An example of visualizing the values of the longitudinal force in the elements at the i- step of the calculation (the deformed scheme)

However, along with the need to consider the possibility of progressive collapse, methods of its prevention also remain the main open question. This is especially relevant for the specific systems which are, in fact, compound shells, as it has been noted earlier. However, it is necessary to ensure adequate commonality of the arched structural elements work. The proposed constructive implementation provides for the installation of bolted joints, as shown in fig. 6.

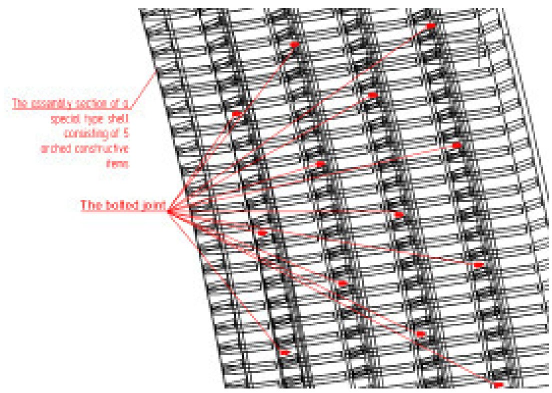


Figure 6 – The proposed constructive implementation of the arrangement of the bolted connection

This modernization enables to ensure the arched structural elements deformations compatibility, and to transform the stress-strain state of a specific composite shell into a stress-strain state close to a continuous ribbed shell, thereby obtaining a discrete-continuous ribbed shell. It is confirmed by comparing and analyzing the stress-strain state and stability of the computational models: a continuous ribbed shell, as well as the above-described discrete-continuous shell (using a bolted joint).

Consideration of qualitative and quantitative results has been carried out in the environment of PC "Lira" (license No. 1/6258), funded by the finite element method [12].

Researches have been conducted on the basis of accepted hypotheses and assumptions:

1. The principles of the shells classical theory are adopted, based on the Kirchhoff-Love hypotheses [13].

2. The torsion and displacements difference of the shell sides elements are not permissible and are not considered. According to the manufacturing technology, the supports are assumed to be articulated and fixed, that is, in the researched FE-models, linear displacements in the nodes of finite elements adjacent to the onboard element are prohibited.

3. Researches have shown that the end diaphragms of cylindrical shells are so rigid that in the majority of cases they can be considered to be non-deformable in their own plane, and from their own plane they are assumed to be absolutely flexible, that is, those ones that do not perceive perpendicular efforts [14]. In order to reduce the dimension of the finite element models under study, the simulation of diaphragm designs has not been performed, and according to the above, at the nodes of finite elements bordering the diaphragm, linear displacements in the plane of the diaphragm, that is, along the global X and Z axes, of the coordinate system of the used software complex have been prohibited.

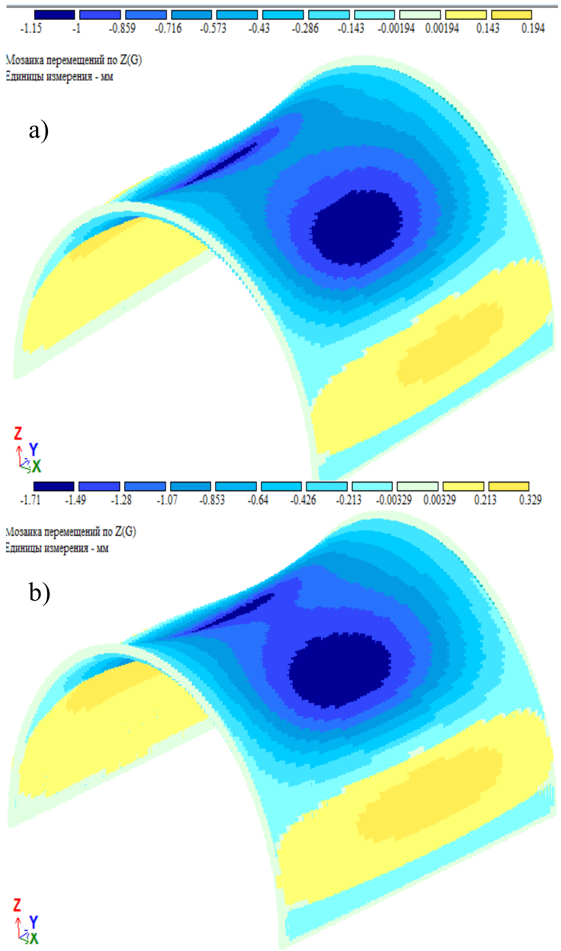


Figure 7 – Displacement along the vertical axis "Z":
a) FE model of a ribbed continual shell;
b) FE model of a modernized special type shell (bolted)

The models of the short shells [15], which have the following geometric ratios, boundary conditions, and features have been researched:

- L = D = 2R, with R = 11.63 meters, H = R, "R" is the radius; "H" is the camber of arch; "D" is the length of the shell;
- Shell thickness t = 1.2 mm;
- In the ribbed shell model, the thickness of the reinforcing rib is equivalent to the double thickness of the shell itself, that is, $t_r = 2t = 2.4$ mm.
- To simulate a bolted joint, the principle is shown in fig. 4, however, instead of the FE 255 (two-nodes finite element of one-sided bonds), the FE10 has been used (universal spatial rod ∅4 mm Stell 235).
- In places where the shell mates with the onboard element - a fixed hinge, that is, linear displacements along the X, Y, Z axes are prohibited in the used global coordinate system of PC "Lira";

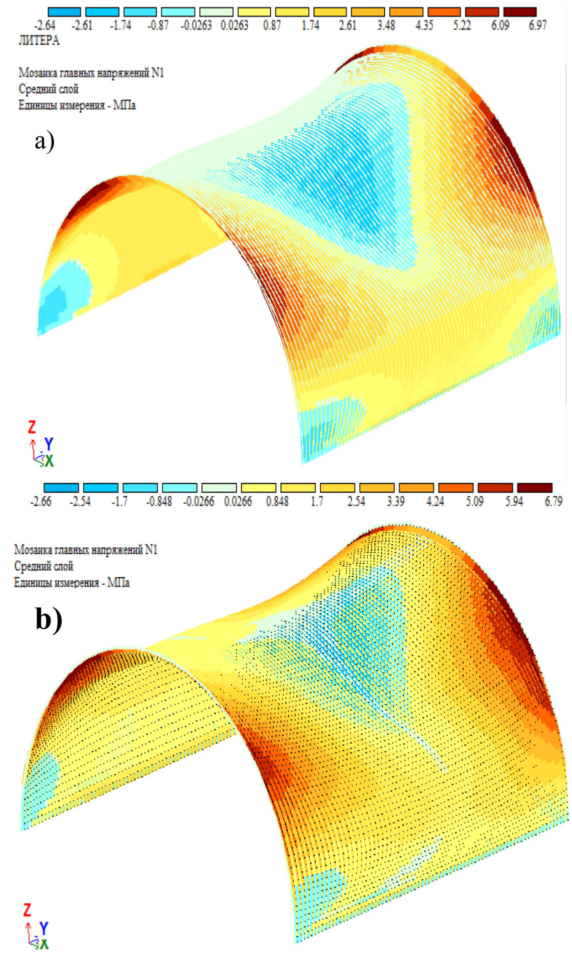


Figure 8 -- Mosaic of distribution the main stresses "σ_1" MPa:
a) FE model of a ribbed continual shell;
b) FE model of a modernized specific shell (bolted)

A uniformly distributed load has been applied, which is equivalent to 0.0015 MPa.

As a result of analyzing the components of the stress-strain state, at the Figures 7–9 it is shown the mosaics of vertical displacements distribution along the vertical (along "Z"), and also the mosaics of the main ones stretch and compress stresses σ1 and σ3.

For a more detailed analysis, for the researched shell models, as well as for the shell model, with similar dimensions and boundary conditions, but the one that reflects the possibility of progressive collapse, and does not contain constructive modernization (that is, using FE 252 - one-way connection) modal analysis and comparison of amplitude-frequency characteristics (AFC) have been done. The comparison of amplitude-frequency characteristics (AFC) of systems is illustrated in the graph of Fig. 10.

Since, as it is known, in most cases, the main criterion for the exhaustion of the shells bearing capacity is buckling. Buckling tasks are closely related to geometrically non-linear problems.

When using the stepping method of calculation, the buckling of the structure denotes the positive definiteness of the equations linearized system matrix. The condition of positive definiteness of a symmetric matrix, according to the Sylvester criterion, is the positivity of all its main minors, which is checked during the elimination of unknowns by the Gauss method [16].

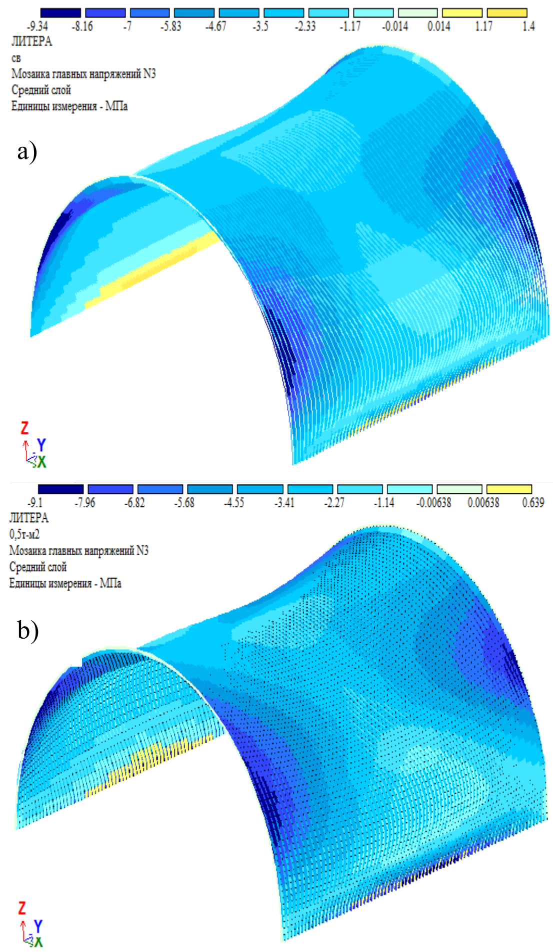


Figure 9 - Mosaic of the main stresses distribution"σ_3" MPa:
a) FE model of a ribbed continual shell;
b) FE model of a modernized specific shell (bolted)

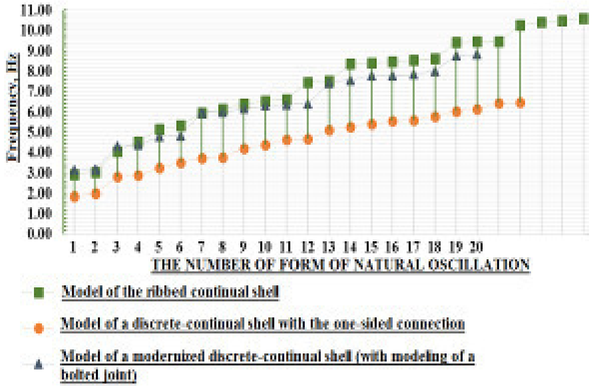


Figure 10 – Graph of the natural frequencies values, depending on the form number

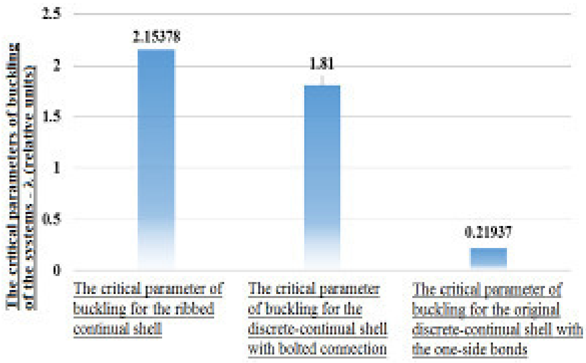


Figure 11 – Diagram of the critical parameters of the systems buckling - λ

This approach enables to research stability while simultaneously considering both geometric and physical nonlinearity. This method of stability research is called the deformed scheme stability method.

The main task of calculating the stability is to determine the critical parameter value of system buckling - λ. The physical meaning of the buckling critical parameter is that if the load on the structure is increased by a factor of λ, the system loses its stability. This version of the design stability assessment assumes that the distribution of forces/stresses is known from the solution of a linear static task and all external forces applied to the system (and as a result, internal forces/stresses) increase in proportion to one parameter λ. A buckling instability occurs when the reduction in force resistance is accompanied by the increase in displacement [17].

The main task is to determine the value of the numerical parameter λ so that at the external forces ($\lambda \times F_0$) there is a buckling. For the researched shells, the buckling factors are presented in the diagram in fig. 11.

Conclusions

After analyzing the vertical displacements of the ribbed continual shell and the modernized special type shell (with bolted connection), which are shown in Fig. 7, it is noted that the nature of the distribution and the value of the displacements have the same order. The value of tensile and compressive stresses "σ1" and "σ3" in the compared shells have almost identical distributions and the same order of value, Fig. 8-9. From the above, it can be concluded that the special type system obtained by constructive modernization (bolting installation) can be considered a discrete-continual ribbed shell while having a sufficiently adequate safety margin compared to other design models. This indicates the rationality of this approach. And the proposed modernization method enables to consider one of the possible options for preventing progressive collapse and increasing the bearing capacity of special type steel shells. As a development of this line of research, a full-scale experiment is planned to assess the impact of constructive modernization on the stress-strain state of discussed structures.

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