Haponova, L. V. (2025). Rationalization of reinforced concrete structural-anisotropic shells design parameters. *Actual Issues of Modern Science. European Scientific e-Journal, 40*, 96–107. Ostrava.

DOI: 10.47451/tec2025-10-02

The paper is published in Crossref, ICI Copernicus, BASE, Zenodo, OpenAIRE, LORY, Academic Resource Index ResearchBib, J-Gate, ISI International Scientific Indexing, ADL, JournalsPedia, Scilit, EBSCO, Mendeley, and WebArchive databases.

Lyudmyla V. Haponova, Candidate of Engineering Sciences (Ph.D.), Associate Professor, Department Head, Department of Computer Graphics, Kharkiv National Automobile and Highway University. Kharkiv, Ukraine.
E-mail: gaplyudmila@gmail.com
ORCID 0000-0002-6038-2624

Article history:
Received: October 16, 2026
Revised: November 22, 2026
Accepted: December 1, 2026
Published: December 14, 2026

Rationalization of Reinforced Concrete Structural-Anisotropic Shells Design Parameters

Abstract:
In the article, the formulation and implementation of the task to rationalize the structural parameters of reinforced concrete structurally anisotropic shells are presented. The criterion for such an objective is the energy principle, according to which it is considered that out of the entire set of possible system parameter values with a constant volume of material, the number of external and internal ties, the potential deformation energy after the reconstruction reaches the lower limit at a rational combination of the geometric parameter values. The coatings of buildings and structures perceive significant loads, which cause a high level of the stress-strain state of the system. That is why it is advisable to consider such types of coatings that could perceive, evenly distribute and transfer the load to the supports. Structurally anisotropic reinforced concrete shells of different Gaussian curvature are proved to be the most suitable for this purpose. The search for rational shell designs that perceive the specified types of loads is a rather urgent, but logically unfinished problem.

Keywords: structurally anisotropic shell, potential deformation energy, self-supporting skeleton, cavity-forming liners, stress-strain state.

Abbreviations:

FEM is finite element method,

PDE is potential deformation energy,

$PDED$ is potential deformation energy density,

SSS is stress-strain state.

Introduction

The design and implementation of enclosed micro-architectural forms represent a salient and pressing concern within contemporary environmental design. This discourse specifically addresses the development of ground-level modular protective shelters engineered to serve as critical infrastructure for the mitigation of blast wave and shrapnel-induced trauma. Such structures are conceived for strategic integration within public nexus points, encompassing transportation termini, designated recreational areas, urban civic spaces, and other open-air gathering locations across diverse residential and commercial landscapes.

Previously scientific studies of the influence between explosion parameters and enclosing structures were conducted (*Ansys simulation software…, n.d.*; *Babaev et al, 2016*; *Bugaevskij, 2015*; *Cormie et al., 2009*; *DBN…, 2023*; *Haponova et al. 2018*). Demonstrating the idea of modeling the stress-strain state of complex objects, it is impossible not to quote A.V. Perelmuter: "The work of the supporting structure is largely determined by the shoulder of the internal pair. In a sphere, it is equal to the distance between the belts, in an arch to the distance from the lock to the tightening, in a dome approximately to the distance between the top and the support ring. And what is the shoulder of the internal pair in a shell of double curvature on a rectangular plan? The answer to this question requires an understanding of the structure's operation "as a whole", which is in many ways the opposite of the practiced detailed SSA. Such analysis is aimed at studying the details (finding stress peaks, places with maximum deflections, etc.)." (*Perelmuter, 2013*) The finite element method is based on the discretization of the object itself, which is represented in the form of individual finite elements (*Haponova et. al. 2015*). At the same time, the introduction of direct methods into the practice of design was facilitated, on the one hand, by the ways of interpreting the very concept of "rational solution", and on the other hand, by the widespread use of the FEM. The concept of "rational design" was somewhat specified and transformed with the help of interesting ideas and research by G.V. Vasylkov and V.S. Shmukler (*Haponova & Hrebenchuk, 2017*). The works of B. Mandelbrot are devoted to modeling geometric parameters considering fractal theory (*Horodeckij et al., 2003*). Anisotropy is distinguished by the following parameters:

1) elastic properties;
2) elastic limits, yield strength, other properties determined in the area of small plastic deformations;
3) characteristics of significant plastic deformation (strength limit in the presence of a neck, uniform plasticity, etc.);
4) characteristics associated with destruction (characteristics of fracture resistance under various types of loading, ultimate plasticity, etc.).

There is a certain distinction between anisotropy of characteristics determined under static loads, anisotropy of long-term strength and creep, anisotropy of impact toughness, crack resistance, hardness and microhardness, etc. By structural feature, anisotropy can be homogeneous and heterogeneous, caused by oriented residual microstresses or associated with the features of the dislocation structure. Many metallic materials are quasi-isotropic in the elastic and plastic areas, as well as during fracture by shear, but anisotropic in resistance to tearing. In sheet materials, a distinction is made between "planar" and "normal" plastic anisotropy. The first is determined by the dependence of the characteristics on the direction in the plane of the sheet, the second is determined by the difference between the properties in the plane of the sheet and the direction perpendicular to it (through the thickness). By geometric nature, a distinction is made between rectilinear and curvilinear anisotropy.

The scientific novelty of the study lies in the development and implementation of an energy-based methodological framework for rationalizing the design parameters of reinforced concrete structurally anisotropic shells with complex geometry. For the first time, the author formulated a numerical optimisation model that establishes dependencies between the PDE and the geometric parameters of both external and internal structure elements under the condition of a constant material volume. The research introduces a vector of control parameters combining external (lifting boom height, curvature radius, span, load) and internal (rib pitch, rib and skin thickness, cross-section height) variables, enabling the identification of rational configurations that minimise PDE.

A distinctive innovation is the integration of the FEM with parametric modelling tools (LIRA SAPR, Autodesk Revit, Dynamo) for automated generation, computation, and optimisation of shell geometry. This approach allows simultaneous evaluation of the structure's SSS and modal characteristics, verifying energy efficiency through natural frequency analysis. Furthermore, the study proposes a technological solution using in-situ concreting with cavity-forming liners to create self-supporting anisotropic frameworks, reducing weight and improving structural resilience.

Thus, the novelty of the work consists in combining energy-rational design criteria, computational modelling, and construction technology into a unified system for optimising reinforced concrete anisotropic shells intended for both civil and protective infrastructure.

The subject of the study is the process of rationalisation and optimisation of design parameters of reinforced concrete structurally anisotropic shells—including their geometric configuration, material anisotropy, and deformation energy characteristics—under static and dynamic loading conditions, based on the application of the energy principle and finite element modelling.

The object of the study is reinforced concrete constructively anisotropic structure.

The study aims to rationalize the design parameters of reinforced concrete constructively anisotropic structures.

To achieve the purpose, the following objectives were defined:

- obtaining dependencies between the PDE and the geometric parameters of constructively anisotropic structures;
- improving the technology of erecting a cylindrical shell;
- cutting out a cavity-forming liner for a self-supporting frame;
- a numerical experiment of a constructively anisotropic structure's behavior when exposed to a uniformly distributed snow load of 1600 Pa/m^2 and a concentrated load of $1t/m^2$.

Study tools are LIRA software complex, Autodesk software products, etc.

Methods

The study employs a multi-level methodological framework combining theoretical, numerical, and experimental approaches to rationalise the design parameters of reinforced concrete structurally anisotropic shells.

At the theoretical level, the research is grounded in the *energy principle* of structural mechanics, assuming that within a system of constant material volume and fixed boundary conditions, the PDE attains a minimum at an optimal set of geometric parameters (*Shmukler, 2017*). This principle guides the analytical formulation of the problem, represented as a dependency function between the deformation energy and external or internal control parameters—such as shell height (H), curvature radius (R), rib spacing (l), skin thickness (δ), and rib thickness (Δ).

The mathematical and computational stage relies primarily on the *finite element method* (FEM) to model the SSS of anisotropic shells. Discretization of the structural domain into finite elements was conducted using the *LIRA SAPR* software package, which allowed the simulation of deformation fields under both uniform (snow) and concentrated loads. The mesh size and element type were calibrated according to convergence tests to ensure numerical stability. Complementary modelling was performed in *Autodesk Revit* and *Dynamo* environments, where visual programming scripts were written to parametrically vary geometric inputs and automatically regenerate shell models.

To validate the energy criterion, the study introduced a parametric control vector containing external (H, B, R, L, q) and internal (l, δ, Δ, h) parameters. By stepwise variation of the lifting boom height (H) and rib pitch (l) under a constant material volume, multiple computational experiments were executed. Each variant produced a unique PDE value, and the resulting unimodal dependency curve was used to determine the rational parameter combination where the PDE reached its lower limit.

The engineering-technological methods included the *in-situ concreting technique*, where cavity-forming liners made of polystyrene were applied to create internal voids in the shell, forming a self-supporting skeleton. This approach ensured the integrity of anisotropic ribs while reducing structural weight. The resulting concrete class was C25/30, meeting current European standards for protective infrastructure.

Additionally, the analytical and experimental validation involved comparison of natural frequency spectra for shells with different geometric configurations. Modal analysis confirmed that the rational configuration ($H \approx 3.8$ m) corresponded to the lowest PDE and highest structural stiffness, thus ensuring the resonance safety of the system.

Finally, the data interpretation stage involved integrating numerical outputs into graphical and tabular forms. The deformation and potential energy fields were visualised as colour-mapped contour plots, providing insight into the uniformity of stress distribution across the shell surface. These results substantiate the theoretical premise that structural rationalisation leads to improved energy efficiency and mechanical resilience.

Literature Review

The theoretical foundation of rationalizing reinforced concrete structural-anisotropic shells has evolved through decades of research in structural mechanics and computational modelling.

The central idea rests on the energy principle, which postulates that a rational configuration of geometric parameters minimises the PDE for a structure of constant material volume and boundary conditions (*Shmukler, 2017*). This principle serves as a critical tool in optimising geometrically complex shell systems where the SSS must remain stable under variable static and dynamic loads (*Perelmuter & Slivker, 2011*).

Early analytical models of stress–strain behaviour in curved and spherical roof shells (*Babaev et al., 2016*) revealed that structural performance largely depends on the “internal pair shoulder”, i.e., the distance between load-bearing belts and support points, which dictates deformation energy distribution. Later studies refined this understanding using FEM discretization, allowing accurate simulation of anisotropic materials with heterogeneous stiffness (*Horodeckij et al., 2003*). The integration of FEM with parametric design software such as LIRA SAPR and Autodesk Revit enabled automatic generation and evaluation of shell geometry (*Kalmykov et al., 2017a*).

Fractal geometry (*Mandelbrot, 2002*) further contributed to the understanding of multi-scale surface anisotropy, providing mathematical tools to simulate non-uniform stiffness patterns in curved elements. This approach supports the structural concept of “constructive anisotropy,” where directional material properties enhance energy dissipation and load redistribution. Haponova and Hrebenchuk (*2018*) expanded on this by developing information-modelling frameworks that link PDE analysis to geometric parameters, making it possible to rationalise shell design digitally.

Experimental studies have confirmed that reinforced concrete anisotropic shells demonstrate superior mechanical stability under combined static and dynamic effects when geometric parameters—such as curvature radius, rib pitch, and shell thickness—are selected according to energy criteria (*Haponova & Hrebenchuk, 2017*; *Kalmykov et al., 2017b*). Further numerical analyses, including studies by Romashkina et al. (*2024*), showed that dynamic load simulations based on blast-wave propagation validate the robustness of rationalised designs in protective engineering contexts.

International standards (*Structures to Resist…, 2008*; *DBN…, 2023*) emphasise the necessity of protective structures capable of absorbing and dispersing energy from accidental or deliberate explosions. The adaptation of these requirements to civil architecture highlights the interdisciplinary importance of anisotropic shell systems as both structural and protective solutions. Consequently, the integration of computational tools, experimental validation, and energy-based optimisation establishes the methodological basis for rational design of reinforced concrete structurally anisotropic shells (*Perelmuter, 2013; Shmukler, 1977*).

Results

Directions for Rationalization of Reinforced Concrete Constructively Anisotropic Structures’ Parameters

Modeling of the stressed-deformed state, geometricity of parameters taking into account the energy principles of anisotropic shells, considered in the number of prominent research papers (*Haponova, & Hrebenchuk, 2018*; *Kalmykov et al., 2017a*; *Kalmykov et al., 2017b*; *Mandelbrot, 2002*; *Perelmuter, 2013*; *Perelmuter & Slivker, 2011*; *Romashkina et al., 2024*; *Shmukler, 1977*; *Shmukler, 2017*; *Structures to Resist…, 2008*; *The Design of Structures…, n.d.*).

Whereas in the current study a fundamentally new type of structure has been investigated, which has a given external and calculated internal geometry; the process of a structurally anisotropic shell deformation under various types of external and internal influences has been mathematically modeled. V.S. Shmukler in his work (*2017*) noted that "for the regulation of systems with a constant volume of material, the number of external and internal connections (external parameters) under the action of a static external load (self-weight) the PDE after restructuring reaches the lower limit at a rational combination of the values of geometric parameters":

$$U = inf_{\alpha} U(\alpha^k), k = 1, 2, \ldots \infty \quad (1)$$

where

U is stands for PDE;

k is comparison option number $\alpha \in M$;

M is set of permissible values of external geometric parameters.

The implementation of the approach entails the construction of a relationship between the magnitude of the system's deformation energy and one or a group of geometric parameters. The formulation of such a problem in numerical form is possible when using computational software complexes, however, the operation entails the construction of a significant number of models, which to some extent complicates the process.

Thus, the formulation and implementation of rationalizing the structural parameters of reinforced concrete cylindrical shells is presented. The criterion for this problem is the energy principle, according to which it is considered that out of the entire set of possible values of the search parameters of the system with a constant volume of material, the number of external and internal connections, the PDE after the restructuring reaches the lower limit at a rational combination of the values of the geometric parameters of the described system.

The vector of control parameters of this system is introduced into consideration:

$$\{x\}^T = \{H, B, V, R, L, l, q, \delta, \Delta, h\} \quad (2)$$

where

H stands for lifting boom;

B is shell length;

V is volume of material;

R is curvature radius;

L is shell span;

l is rib pitch;

q is external load;

δ is thickness of the skins;

Δ is thickness of the ribs;

h is shell cross-section height.

In this case, the parameters H, B, R, L, q are positioned as external, and the parameters l, δ, Δ, h as internal. The step of the inner ribs of the shell l is taken as variable parameters. The remaining attributes of the calculation model are set by analogy, with the exception of the thickness of the skin δ, which in this case is taken equal to 50 mm, and the lifting boom H, taken as 3.8 m. The constancy of the material volume in this case was ensured by selecting the appropriate value of the thickness of the ribs Δ.

Thus, the proposed approach opens up the possibility of determining rational parameters of reinforced concrete structurally anisotropic elements with complex external and internal geometry. The above analysis is expanded by studying the distribution of the strain energy density (internal parameter). In this case, the criterion will be the dependence:

$$e \to const, \tag{3}$$

where

e is the PDED.

The alignment of the PDE field (LIRA software package) is implemented by giving the cavity-forming insert a complex shape. In this case, the grid of ribs is not orthogonal. The potential energy density field of the ribs in a cylindrical shell with a span of 9000 mm is shown in Figures 1–4 (*Appendix*).

Improving the Structural Characteristics of Constructively Anisotropic Structures

The work implements numerical methods for solving the problem using the example of a cylindrical shell with internal cavities of a rectangular shape in plan (*Figure 5*). An analysis of studying the external parameters of a cylindrical reinforced concrete anisotropic shell with internal cavities formed by polystyrene foam inserts (*Figure 6*) has been performed.

As a tool for solving the problem, a combination of Autodesk software products was used. The fundamental issue here is a script written in a visual programming environment, which allows you to automatically form the geometry of the shell by setting all the necessary parameters from the number $\{x\}$.

The proposed procedure allows you to automatically build a connection between the PDE of the system and any geometric parameter that describes it. As an illustration, examples of searching for external and internal rational parameters of the shell are considered.

When analyzing external parameters, the lifting boom is taken as a variable $H \in (H\,[0;\,L/2])$, other parameters describing the geometry of the system are taken as follows: B = 9000 mm; L = 18000 mm; h = 300 mm, Δ = 100 mm; l = 1000 mm. The load was taken as the self-weight, the support was designed as hinged fixed along two longitudinal ribs, the material was concrete C25/30. Stepwise change of the parameter H (lifting boom) allowed it to determine its relationship with the value of the system PDE, while in all cases the volume of the shell material was unchanged. Stability was ensured by selecting the appropriate value of the shell thickness δ. The calculation results are given in Table 1 (*Appendix*).

Based on the obtained data, a graph of the dependence of the PDE on the lifting boom H was constructed, which represents a unimodal function. It was determined that for the tasks of conditions at $H \approx$ 3,8 m the PDE reaches the lower limit. The obtained results are verified by analyzing the natural frequencies of the system for all values of H and estimating the maximum load-bearing shell capacity (q_{max}). The 7 out of 10 tones of natural oscillations take on a maximum value at a value of H close to rational.

In case of achieving equivalent stresses of the system (σ_e) the strength limit of the material is determined—q_{max} for the optimal value H_i values, 1 m more or less than the rational (4,8 and 2,8 m respectively): at H = 3,8 m and q_{max} = 38,45 kN/m^2; at H = 4,8 m and q_{max} = 35,15 kN/m^2; at H = 2,8 m and q_{max} = 30,26 kN/m^2.

The natural frequencies of structurally anisotropic shells are shown below in Figures 7–10 (*Appendix*).

Discussion

The study addresses an increasingly urgent challenge in structural engineering and civil protection—developing lightweight yet resilient reinforced concrete shells optimised through energy-based criteria. The significance of this study lies in its synthesis of classical mechanics, computational modelling, and protective design principles to achieve rational geometrical configurations for structurally anisotropic systems.

The findings confirm the hypothesis that structural rationalisation based on the minimisation of PDE produces configurations with enhanced stiffness and stability under both static and dynamic loads. The discovered rational parameters (e.g., $H \approx$ 3.8 m, $l \approx$ 1000 mm) correspond to conditions where PDE attains its minimum and the natural frequencies reach their optimal values, thereby improving both energy performance and vibration safety.

However, the research also revealed several methodological challenges. The high computational complexity of modelling anisotropic shells with variable geometry necessitates extensive simulation runs and fine mesh refinement, which may increase processing time and require advanced software integration. Furthermore, the assumption of homogenous material behaviour within anisotropic systems introduces limitations when scaled to real-world structures, where micro-heterogeneity and construction tolerances affect performance.

Another identified issue concerns the practical realisation of cavity-forming liners. While polystyrene inserts effectively reduce weight and ensure geometric stability, their long-term durability under cyclic loading and environmental influence warrants further investigation. Future research should thus focus on developing alternative eco-friendly liner materials and improving the recyclability of such components.

The study opens several promising research directions. First, extending the FEM-based framework to include *nonlinear dynamic analyses* could provide more accurate simulations of blast-wave impacts and seismic responses. Second, integrating *machine-learning algorithms* for parameter optimisation may significantly reduce computational effort. Finally, collaboration with industrial partners could facilitate pilot construction of modular anisotropic shelters for civil defence and urban safety applications.

Overall, this work contributes to advancing energy-based design methodologies for complex shell systems and underscores their critical role in creating adaptive protective structures in the context of modern geopolitical and environmental challenges.

Conclusion

The energy criterion for rationalization of external structural parameters of reinforced concrete structurally anisotropic shells was applied. According to the results of the study, it was determined that for the considered specific conditions at $H \approx$ 3.8 m the potential energy of deformation reaches the lower limit.

The obtained results were verified by analyzing the frequencies of natural oscillations of the system for all values of the lifting boom (H) and the maximum bearing capacity (q_{max}) of the shell was estimated.

The relationship of rational parameters in the structurally anisotropic shell between the PDE of the system for external and internal rational parameters was determined: at a rib pitch close to $l \approx 1000$ mm the PDE reaches the lower limit.

And there is currently a substantial demand for these. In response to the current geopolitical landscape, specifically the unprovoked military aggression by the Russian Federation against Ukraine, there is an urgent and critical need for enhanced protective infrastructure. This imperative has driven significant improvements in the technologies underpinning small-scale architectural forms, leading to the creation of compact, ground-based modular shelters. These structures are engineered to provide civilians with vital protection against the traumatic effects of blast waves and shrapnel. Their strategic integration into high-traffic public environments—including public transportation points, recreational parks, urban plazas, and various open communal spaces within both population centers and industrial territories—represents a timely and essential intervention for safeguarding the populace of our country and its cities.

Funding

No external funding was received.

Conflict of Interest

The author declares that there is no conflict of interest.

Acknowledgements:

Not applicable.

References:

Ansys simulation software enables organizations to confidently predict how their products will operate in the real world. (n.d.). *Ansys, Inc.* www.ansys.com

Babaev, V. N., Shmukler, V. S., Feirushah, S. H., Gaponova, L. V., Grebenchuk, S. S., Kalmikov, O. A. (2016). Analysis of Stress-Strain State of Spherical Roof Shell. *The 1st International Conference on Engineering and Innovative Technology*, 42–49 (SU-ICEIT 2016; April 12-14). Kurdistan: Salahaddin University-Erbil.

Bugaevskij, S. A. (2015). Method of construction elements of a curved. *Scientific Bulletin of Construction*, *2*, 116–126. (In Ukr.)

Cormie, D., Mays, G., & Smith, P. D. (2009). *Blast effects on buildings* (2nd ed.). London: Thomas Telford.

DBN V.2.2–5:2023. (2023). Kyiv: Minregion Ukrayini. (In Ukr.)

Haponova, L. V., & Hrebenchuk, S. S. (2017). Stress and strain behavior of reinforced concrete anisotropic shell. *Academic Journal. Series "Industrial Machine Building, Civil Engineering"*, *1*(48), 108–120. Yuri Kondratyuk Poltava National Technical University. (In Ukr.)

Haponova, L., & Hrebenchuk, S. (2018). Information modeling in the rationalization of the parameters of iron concrete construction anisotropic shell. Sustainable housing and human settlement: Monograph. Moscow, Dnipro, Bratislava: Prydniprovska State Academy of Civil Engineering and Architecture, Slovak University of Technology in Bratislava (pp. 188–199).

Haponova, L., Hrebenchuk, S., Psurtseva, N., Kalmykov, O., & Demyanenko, I. (2018). Features of modeling of energy profile of construction. *The 7th International Scientific Conference "Reliability and Durability of Railway Transport Engineering Structures and Buildings"*, 02009. Kharkiv. (In Ukr.)

Haponova, L. V., Kalmikov, O. O., & Grebenchuk, S. S. (2015). Experimental and theoretical sustainability of a research on the stress-strain state of a spherical shell covering. *Collection of Scientific and Practical Works of the Ukrainian State University of Railway Transport*, *157*, 102–113. Kharkiv. (In Ukr.)

Haponova, L. V., Reznik, P. A., & Grebenchuk, S. S. (2017). Evaluation of the fire resistance of a structurally anisotropic reinforced concrete slab. *Interdepartmental Scientific and Technical Collection (Technical Sciences) "Construction Production"*, *62/1*, 57–63. (In Ukr.)

Horodeckij, A. S., Shmukler, V. S., & Bondarev, A. V. (2003). *Information technologies for calculation structures*. Kharkiv: NTU «HPI». (In Ukr.)

Kalmykov, O., Gaponova, L., Reznik, P., & Grebenchuk, S. (2017a). Study of fire-resistance of reinforced concrete slab of a new type. *The 6th International Scientific Conference "Reliability and Durability of Railway Transport Engineering Structures and Buildings MATEC Web Conference*, *116*. (In Ukr.)

Kalmykov, O., Gaponova, L., Reznik, P., & Grebenchuk, S. (2017b). Use of information technologies for energetic portrait construction of cylindrical reinforced concrete shells. *The 6th International Scientific Conference "Reliability and Durability of Railway Transport Engineering Structures and Buildings MATEC Web Conference*, *116*. (In Ukr.)

Mandelbrot, B. (2002). *Fractal geometry of nature*. Institute of Computer Research.

Perelmuter, A. V. (2013). *Notes on structural science*. Computational Civil and Structural Engineering. (In Ukr.)

Perelmuter, A. V., & Slivker, V. I. (2011). *Calculated models of structures and the possibility of their analysis*. ASV. (In Ukr.)

Romashkina, M., Pisarevsky, B., & Zhuravlov, O. (2024). Development of a construction plan for the introduction of a construction plan for the introduction of a wind-blown impact wave by a direct dynamic method with the winners of the LIRA-SAPR. *Collection of Scientific Practices "Construction Designs. Theory and practice"*, *14*, 147–160. Kyiv. (In Ukr.)

Shmukler, V. S. (1977). *Study of the work flat shallow concrete shells* [Dissertation of Candidate of Technical Sciences, Kyiv]. (In Ukr.)

Shmukler, V. S. (2017). New energy principles of design rationalization. *Collection of Scientific Papers of the Ukrainian State University of Public Transport*, *167*, 54–69. (In Ukr.)

Structures to Resist the Effects of Accidental Explosions (UFC 3-340-02). (2008). U.S. Department of Defense (DOD). Washington, DC.

The Design of Structures to Resist the Effects of Accidental Explosions-Technical Manual (TM 5–1300). (n.d.). U.S. Department of the Army, the Navy and Air Force.

Appendix

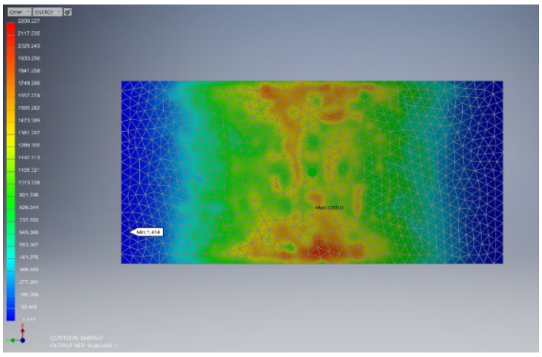

Figure 1. The potential energy density field of the shell ribs, depending on the pitch with a span of 9000 mm with a boom height of 2250 mm, rib pitch of 500 mm and rib thickness of 50 mm.

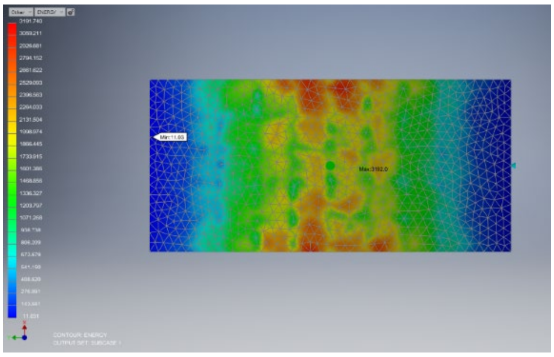

Figure 2. The potential energy density field of the shell ribs, depending on the pitch with a span of 9000 mm with a boom height of 2250 mm, rib pitch of 2000 mm and rib thickness of 166.9 mm.

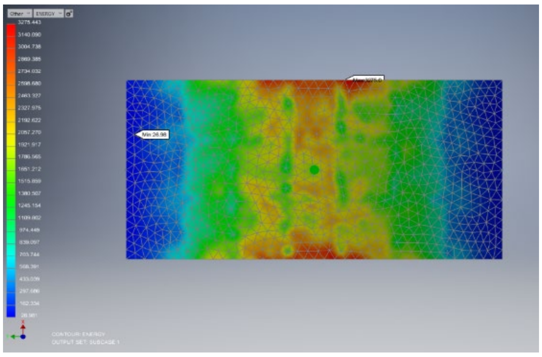

Figure 3. The potential energy density field of the shell ribs, depending on the pitch with a span of 9000 mm with a boom height of 2250 mm, rib pitch of 2000 mm and rib thickness of 241.1 mm

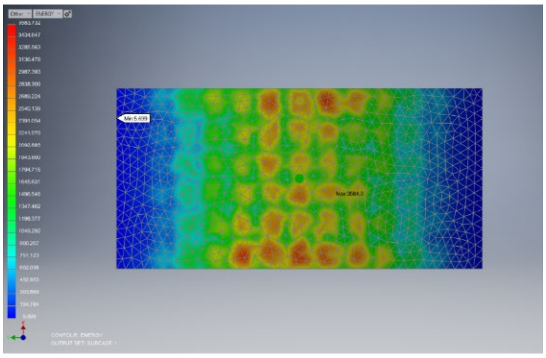

Figure 4. The potential energy density field of the shell ribs, depending on the pitch with a span of 9000 mm with a boom height of 2250 mm, rib pitch of 1500 mm and rib thickness of 137.7 mm

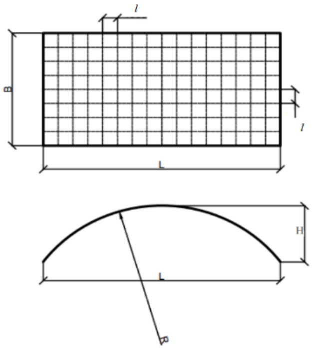

Figure 5. Geometric parameters of the structurally anisotropic shell

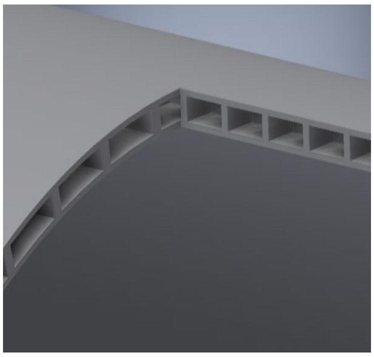

Figure 6. Structurally anisotropic shell made of reinforced concrete

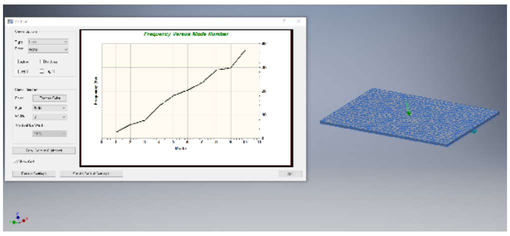

Figure 7. Natural frequencies of a structurally anisotropic shell with a plan size of 9000×10 mm

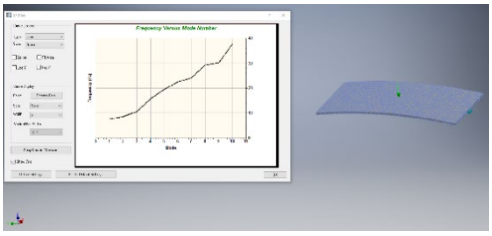

Figure 8. Natural frequencies of a structurally anisotropic shell with a plan size of 9000×1000 mm

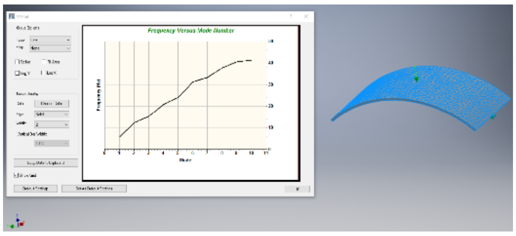

Figure 9. Natural frequencies of a structurally anisotropic shell with a plan size of 9000×3500 mm

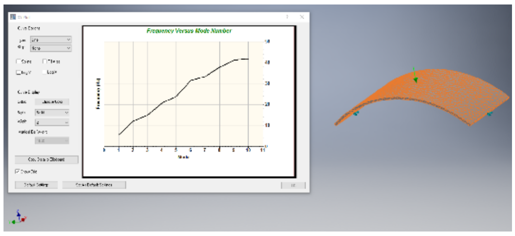

Figure 10. Natural frequencies of a structurally anisotropic shell with a plan size of 9000×3600 mm

Table 1. Calculation results

Lifting boom H, m	Volume of material V, m^3	Curvature radius R, m	Thickness of skins δ, m	Arc length, m	PDE systems U, per unit
0	22,8915	∞	0,0506	18,0000	5,75E + 06
1	22,8915	41	0,0500	18,1478	4,87E + 05
2	22,8915	21,25	0,0473	18,5869	1,30E + 05
3	22,8915	15	0,0450	19,3050	7,57E + 04
4	22,8915	12,125	0,0407	20,2839	6,93E + 04
5	22,8915	10,6	0,0357	21,5010	9,38E + 04
6	22,8915	9,75	0,0315	22,9321	1,55E + 05
7	22,8915	9,285	0,0271	24,5530	2,83E + 05
8	22,8915	9,0625	0,0224	26,3408	5,77E + 05
9	22,8915	9	0,0187	28,2743	1,12E + 06