

Two thin-walled glass domes in the form of a spherical segment with a truncated apex have been considered in this study. The task addressed relates to the lack of experimentally confirmed data on their stressed-strained state and fracture mechanisms, which compromises the reliability of numerical models and limits practical application.

This paper reports experimental results from testing glass dome models subjected to uniformly distributed loading, as well as and their numerical verification using the finite element method implemented in Siemens Simcenter Femap with NX Nastran (USA). The deformation behavior, ultimate load levels, and brittle explosive failure mechanism with crack initiation in the apex zone were identified. The maximum experimental vertical displacement reached 3.1 mm, while the discrepancy between numerical and experimental results did not exceed 12.9%, confirming the adequacy of the numerical model.

The results made it possible to identify tensile stress concentration zones and demonstrated consistency between numerically predicted critical regions and the experimentally observed failure pattern. This was achieved through a combined approach integrating controlled laboratory testing and detailed spatial FEM analysis. The results are attributed to the predominantly membrane behavior of the dome and local stress concentration in the load application zone.

The findings could be applied in the design of transparent dome structures as well as annealed and additively manufactured glass shells intended for special operating conditions, including prospective hermetic modules for extraterrestrial environments such as Mars

Keywords: glass dome; stressed-strained state; Siemens Simcenter Femap; Martian structures, structural behavior of glass structures

DETERMINING REGULARITIES IN THE STRESSED-STRAINED STATE OF A GLASS DOME

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1. Introduction

The evolution of architecture and civil engineering has been accompanied by the active use of translucent spatial structures in public, commercial, and infrastructure buildings. A special place is taken by glass dome systems, which combine architectural expressiveness, functionality, and a high level of natural lighting, which is of great importance for the energy efficiency at modern facilities [1, 2].

The use of glass as a load-bearing material in spatial shells is associated with technical difficulties due to its brittle fracture and high sensitivity to surface defects. In addition, the operation of the structure is affected by geometric imperfections and features of structural units, which change the nature of stress distribution [3–5]. Such difficulties significantly complicate the prediction of the stressed-strained state of complex curvilinear structures and require experimental verification of calculation models.

In previous studies [1, 6], the mechanical behavior of multilayer glass columns, in particular under central compression,

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was investigated using the digital image correlation method, which allowed for the accurate determination of the full strain and stress vector in brittle materials [6]. This created the basis for further expansion of experimental studies to spatial systems such as domes where the geometry and boundary conditions change the nature of the structure's operation as a whole.

A separate promising area of modern research is the use of glass spatial shells in extraterrestrial infrastructure projects, in particular for the construction of protective dome structures on the surface of Mars and other planets [7, 8]. Such structures are considered as the basis for the formation of hermetic residential and research modules using local resources and additive technologies. Previous work has analyzed the possibilities of using 3D printing to form glass dome structures under Martian conditions and substantiated the feasibility of combining experimental and numerical methods to ensure their reliability [9].

The available experimental results for complex glass shells are limited, especially for dome models with registration of local effects and global deformation behavior [10]. This complicates the practical application of theoretical and

numerical models in design calculations, in particular for predicting mechanisms of loss of bearing capacity and establishing critical stress concentration zones.

Conducting experimental studies of glass dome models allows one to clarify the real stressed-strained state under the action of loads, identify critical sections of the structure, as well as obtain verified data for further improvement of calculation methodologies. Such data are an important prerequisite for designing reliable structural solutions and increasing the safety of operation of complex translucent structures.

Thus, the growth in the scale of application of glass dome structures, the difficulty in predicting their stressed-strained state, as well as the need to ensure a high level of operational reliability, predetermine the relevance of specialized experimental studies in this field. Therefore, studies that aim to experimentally investigate the stressed-strained state of glass dome models are relevant.

2. Literature review and problem statement

Review of current scientific papers indicates a growing interest in the study of glass shells and dome structures as promising elements of translucent building systems [11, 12]. However, those studies considered exclusively flat panel configurations. The influence of the curvature of the element on the stress distribution and dynamic strength was not analyzed, which limited the applicability of the results to spatial systems.

Studies [13, 14] report the results from numerical and experimental analyses of the mechanical behavior of curved and multilayer glass elements, which made it possible to establish general patterns of their deformation under load. However, those studies did not consider the influence of real mechanical characteristics of glass on the stressed-strained state of spatial shell structures. The analysis was limited to flat or uniaxially curved elements. The influence of geometric imperfections and fastening conditions on the test results was not considered.

In [15], the dynamic behavior of curved glass panels under low-velocity impact was experimentally investigated. Attention was on the integral characteristics of strength and stiffness, while the detailed analysis of local stresses, geometric imperfections, and the influence of fastening nodes remained limited. That reduced the accuracy of predicting the performance of spatial glass shells under real operating conditions.

The use of non-contact measurement methods, in particular the digital image correlation method, has demonstrated high efficiency for studying deformations and fragmentation in glass structures [16]. However, in the cited work, the registration was performed for flat or rod structures. Experimental studies of dome systems with full registration of spatial deformation fields remained isolated.

In papers tackling the construction of extraterrestrial structures [17, 18] the feasibility of using shell and dome forms for residential modules on the Moon and Mars is substantiated. At the same time, those studies are mainly conceptual or numerical in nature and are not accompanied by sufficient experimental verification. Experimental verification of the bearing capacity of dome forms was not carried out. The issue of local stresses in the fastening nodes and geometric imperfections was not considered.

Theoretical approaches to determining the effective stiffness of multilayer glass elements [19, 20] provide a reliable basis for calculating plates and beams. However, the possibility of their direct application to curved shells required ad-

ditional justification. Both models were developed for planar configurations. They did not take into account the specificity of the biaxial stress state of dome systems.

The influence of geometric imperfections, fastening conditions, as well as technological deviations in manufacturing, on the mechanisms of loss of their bearing capacity remains insufficiently studied. The lack of systematic experimental studies of glass dome models with detailed registration of the spatial stressed-strained state may be due to the complexity of manufacturing physical models of spatial shells, the high cost of experimental equipment, and the limited capabilities of conventional measuring methods.

Summarizing the above, we can formulate an unsolved scientific problem related to the absence of a comprehensive experimentally substantiated methodology for studying the stressed-strained state of glass dome models using modern non-contact technologies and taking into account real design and technological factors. It is the solution to this problem that determines the direction of this study.

All this allows us to assert that it is advisable to conduct a study aimed at establishing regularities in the formation of the stressed-strained state of a glass dome based on experimental tests and their numerical verification by the finite element method. This will ensure an increase in the reliability of predicting the operation of glass dome structures and substantiating their design parameters.

3. The aim and objectives of the study

The aim of our study is to establish regularities in the formation of the stressed-strained state of a glass dome. This will provide an opportunity to substantiate the design parameters of glass dome shells, in particular for the construction of hermetic translucent modules under extraterrestrial conditions, including promising Martian infrastructure.

To achieve the goal, the following tasks were set:

- to experimentally investigate the deformation behavior and nature of the destruction of the glass dome;
- to compare the obtained experimental results with the results of numerical analysis performed by the finite element method.

4. The study materials and methods

The object of our study is two thin-walled glass domes in the form of a spherical segment with a truncated apex. The principal hypothesis assumes that local thickening in the apex zone and a rationally selected cut diameter reduce stress concentration without significantly disrupting the membrane operation of the shell. The study adopts material homogeneity and load symmetry; numerical modeling does not take into account surface defects and long-term deformation effects.

For experimental studies, two identical models of glass domes K1 and K2 (K – glass dome; 1, 2 – sample number) in the form of a spherical segment with a truncated apex were manufactured by glass blowing. The outer diameter of the dome was 195 mm, the total height was 155 mm, the diameter of the upper cut was 85 mm, which forms a flat area in the apex zone in order to reduce stress concentration at the point of load application (Fig. 1). The thickness of the dome is 3 mm and there is a local thickening in the upper cut area with a thickness of 6 mm.

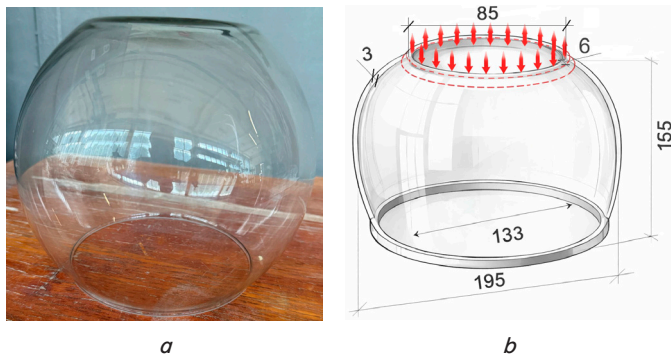


Fig. 1. Model of a glass dome in the form of a spherical segment with a truncated vertex: *a* – side view; *b* – geometric dimensions of the glass dome imagined with Al

The size of the upper section of the dome $D_t = 85$ mm was chosen taking into account the need to reduce local contact stresses in the load application zone and to ensure the reliability of experimental results [21].

Chemical analysis of the glass used for the manufacture of experimental domes revealed the following oxide composition (wt. %): $\text{SiO}_2 - 70.9$; $\text{Al}_2\text{O}_3 - 1.8$; $\text{Na}_2\text{O} - 14.5$; $\text{MgO} - 3.5$; $\text{CaO} - 9.0$; $\text{SO}_3 - 0.27$. The coefficient of linear thermal expansion of glass – $A = 8.7 \cdot 10^{-6}/^\circ\text{C}$. According to the given indicators, the material belongs to sodium-calcium-silicate glass, which is a typical glass for applications as a load-bearing element.

As shown in studies [22, 23], the local stress concentration in spherical and dome shells significantly depends on the geometry of the contact zone. Increasing the contact area leads to a decrease in the average contact pressure and a decrease in the risk of local failure. At the same time, an excessive increase in the diameter of the loading pad can cause a change in the nature of the membrane work of the shell and an increase in bending effects in the transition zone [24].

Studies of experimental methods for testing thin-walled structures [25] indicate that the optimal size of the contact pad should provide a decrease in local stresses without significant distortion of the global stressed-strained state.

Thus, the adopted size of the cut top $D_t = 85$ mm is a rational compromise between the need to reduce contact stresses and preserve the characteristic spatial work of the dome shell.

A special bench for testing glass domes was designed for conducting experimental studies (Fig. 2). The external load N was applied step by step using a hydraulic jack. The magnitude of one load stage was 1.0 kN and was controlled by the readings from the DOSM-3-50U dynamometer until the complete destruction of the experimental sample. At each load stage, a 5-minute hold was carried out, after which the readings of the measuring instruments were read.

The study assumed isotropic and homogeneous glass and symmetry of the applied load relative to the dome axis. Tangential stresses were not directly measured experimentally and were determined from the results of numerical modeling using the finite element method.

To prevent local chipping and damage to the glass in the areas of contact with the metal elements of the bench, a layer

of felt was laid between the sample and the supporting surfaces, which ensured uniform load transfer conditions.

The dome displacements were measured using five dial indicators with a resolution of 0.01 mm. The placement of the measuring instruments was chosen in such a way as to ensure the registration of both axial and radial deformations of the shell in the most stressed areas. The layout of the measuring instruments is shown in Fig. 3.

The proposed loading scheme and displacement measurement system provided the possibility of a comprehensive assessment of the deformation behavior of the glass dome at all stages of loading – from the initial elastic deformation to the moment of loss of bearing capacity. The combination of step-by-step loading, holding at each stage, and multi-point displacement control made it possible to minimize the influence of random factors and increase the reliability of the resulting experimental data. This approach created a reliable basis for further analysis of the stressed-strained state, establishing characteristic stages of the dome shell operation and comparing experimental results with theoretical and numerical models.

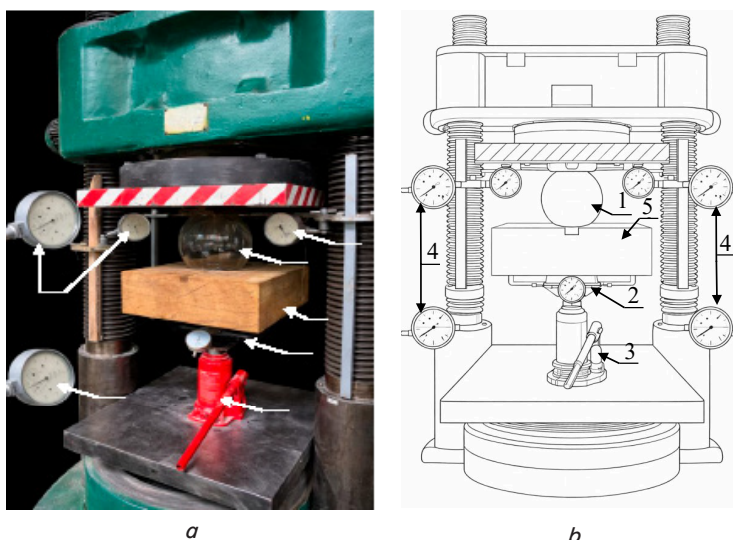


Fig. 2. Testing set-up for experimental glass domes: *a* – view of the test rig; *b* – diagram of the test rig; 1 – prototype being tested; 2 – dynamometer DOSM-3-50U; 3 – hydraulic jack; 4 – clock-type indicators; 5 – wooden bench

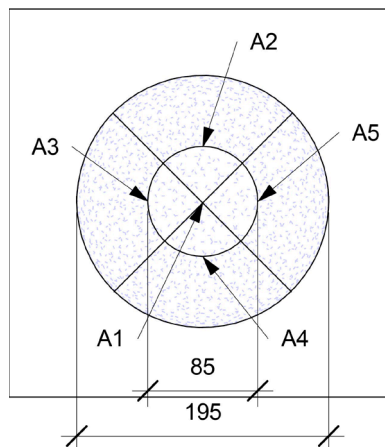


Fig. 3. Layout of measuring instruments: A1 – vertical displacement measurement point; A2–A5 – horizontal displacement measurement points

To determine the calculated values of displacements and stresses, a calculation model was built using the Siemens Simcenter Femap with NX Nastran software package (Fig. 4).

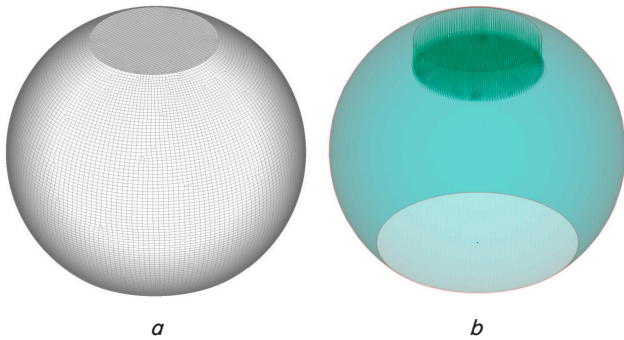


Fig. 4. Calculation model of a glass dome: *a* – calculation scheme; *b* – load application scheme

Siemens Simcenter Femap with integrated NX Nastran calculation module is a modern software package for performing numerical analysis by the finite element method, which is widely used in engineering practice to study the stressed-strained state of structures with complex geometry [26, 27]. The program provided the construction of high-precision finite element models, setting realistic boundary conditions and loads, as well as conducting linear, nonlinear, and stability analyses. The combination of a convenient FEMAP preprocessor interface with a powerful NX Nastran calculation core allows one to effectively model spatial shell glass structures, perform detailed analysis of stresses, deformations, and loss of bearing capacity, as well ensure high reliability of results [28].

The model consisted of nodes and finite elements that reproduced the geometric and stiffness characteristics of the shell.

A plane shell finite element was used to model the thin-walled shell, which allowed us to determine the stressed-strained state of the structure taking into account membrane and bending deformations.

The calculation scheme included 17,291 finite elements and 17,294 nodes. The shell was divided into elements taking into account the surface curvature and geometric features of the structure. The shell thickness in the model was taken to be 3 mm over the entire area of the glass dome and 6 mm in a local zone from the top of the dome with a diameter of 85 mm.

5. Results of the stressed-strained state of the glass dome

5.1. Experimental study of deformation behavior and destruction of the glass dome

The experiment allowed us to establish the nature of the destruction of the experimental dome samples, which is shown in Fig. 5. The destruction of two dome models occurred at a load of the first one $N_1 = 1940 \text{ kN/m}^2$ and the second one $N_2 = 1960 \text{ kN/m}^2$.

The destruction of both domes had a brittle, explosive nature, typical of monolithic glass operating under conditions of complex spatial stress. The upper part of the domes, after reaching the limiting load, completely fragmented into separate fragments of different sizes, without preserving the integrity of the shell.



Fig. 5. Brittle fracture of the glass dome with crack initiation in the upper zone

The fragments clearly showed the radial-meridional nature of crack formation: the cracks began in the apex zone of the dome – in the area of load application – and propagated towards the periphery. This indicated a local concentration of the main tensile stresses in the inner layers of the shell near the upper platform.

The presence of fragments with a smooth curvature confirms that the destruction occurred without prior plastic redistribution of stresses, namely by instantaneous crack growth after exceeding the tensile strength of the glass. The absence of large integral segments of the shell indicated the rapid propagation of cracks throughout the entire thickness of the glass and the loss of the bearing capacity of the dome as a whole.

Thus, the recorded nature of the fracture corresponds to the brittle fracture of the thin-walled glass dome shell, initiated in the zone of maximum contact and membrane stresses in the top part of the structure.

Based on the results of experimental studies, displacement plots were constructed (Fig. 6).

The plot (Fig. 6) shows the experimental dependences of the vertical displacements of the top zone of the glass dome on the uniform uniformly distributed load for two tested samples of the K-1 and K-2 brands. The maximum experimentally recorded displacement at point A1 (Fig. 3) was 3.1 mm. Both curves are similar in nature, which indicates the reproducibility of the experimental results and the stability of the deformation behavior of the dome structures. With increasing load, an almost linear increase in vertical displacements was observed, and minor deviations between the curves may be due to technological differences in the manufacture of samples and local geometric imperfections.

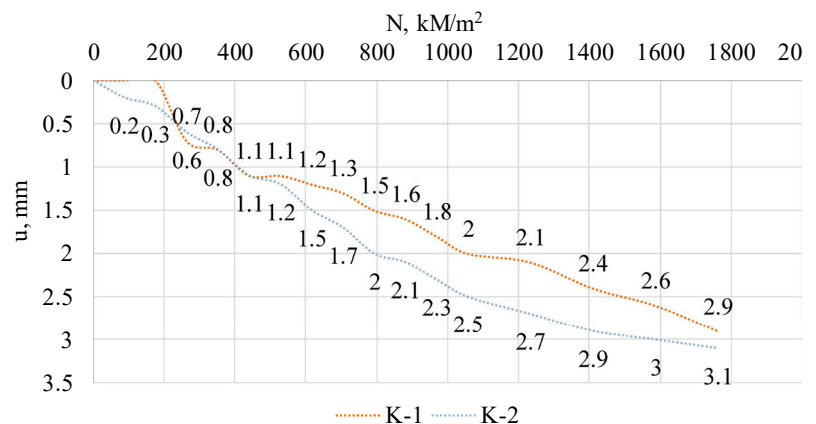
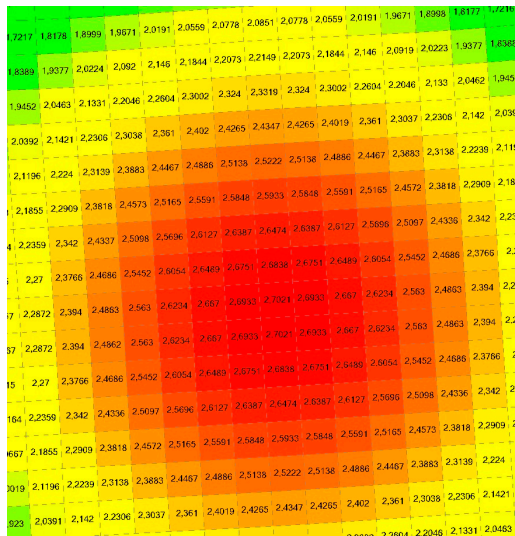


Fig. 6. Dependence of vertical displacements *u* on the level of applied load *N* for glass dome models of brands K-1 and K-2

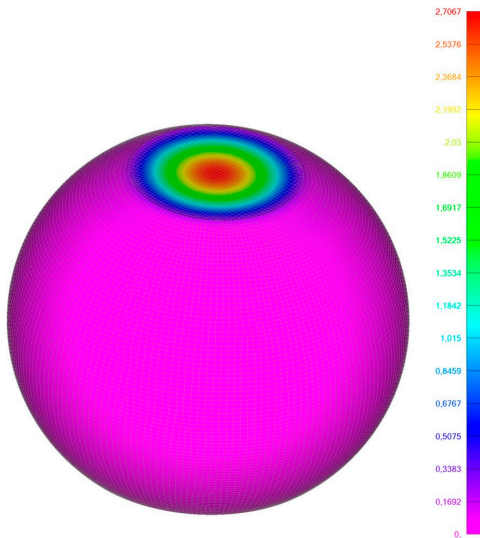
5. 2. Comparison of experimental results with numerical analysis by the finite element method

Based on the constructed computational model of the dome using the Siemens Simcenter Femap with NX Nastran software package, the calculated values of the node displacements were obtained (Fig. 7). Fig. 7 shows results of the numerical analysis of the vertical displacements of the experimental model of the glass dome. Fig. 7, *a* shows a mosaic of the numerical field of the vertical displacements of the nodes of the computational model, which allows a detailed assessment of the distribution of deformations at discrete points of the grid. Fig. 7, *b* depicts the spatial color distribution of the vertical displacements of the dome shell, which clearly illustrates the concentration of maximum displacements in the apex zone of the dome in the area of load application and their gradual decrease towards the support ring. The results reflect the characteristic membrane-bending work of the shell.

The results of the obtained theoretical displacements at point A1 are shown in Fig. 6.



a



b

Fig. 7. Mosaic of displacements of the experimental dome model: *a* – numerical field of vertical displacements of nodes of the computational model; *b* – spatial distribution of vertical displacements of the dome shell

The difference between the maximum calculated (2.7 mm) and experimental (3.1 mm) displacement values at point A1 is about 12.9%, which indicates a satisfactory agreement of the numerical model with the experiment.

The results from numerical calculations determined the magnitude and nature of the stresses in the finite elements of the calculated dome model (Fig. 8).

Analysis of our results has made it possible to establish that the zones of the largest significant stresses (Fig. 8) coincided with the experimental fracture cross-section of the test specimens (Fig. 5). At a load of $N = 1960 \text{ kN/m}^2 (N_u)$, the maximum tensile stresses were 53.8 MPa, which is 19.56% higher than the standard resistance of annealed glass of 45 MPa according to DSTU EN 16612. The influence of the deformable felt layer was not taken into account in the numerical model, which partially explains the difference between the experimental and FEM results.

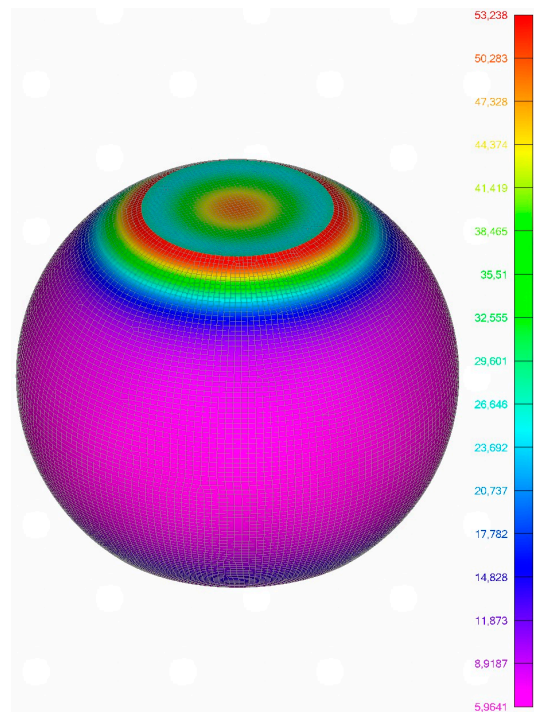


Fig. 8. Stress characteristics of the experimental dome model

6. Discussion of regularities in the stressed-strained state of a glass dome

Experimental studies have shown that the fracture of a glass dome has a brittle, explosive nature, typical of monolithic glass operating under conditions of a complex spatial stress state. Crack initiation occurred in the apex zone of the dome (Fig. 5), where the maximum membrane tensile stresses and local contact stresses from the application of the load were combined. Further radial-meridional propagation of cracks to the support ring indicates the dominance of tensile stresses on the outer surface of the shell.

The experimental “load-displacement” dependences (Fig. 6) were almost linear until the moment of fracture, which indicated the predominantly elastic operation of the dome shell. The close shape of the curves for the twin samples of grades K-1 and K-2 confirms the reproducibility of the results and the stability of the deformation behavior. Small differences between the curves are explained by technological manufacturing deviations and

local geometric imperfections. The maximum experimental vertical displacement at the vertex point A1 was 3.1 mm.

Numerical analysis performed in the Siemens Simcenter Femap with NX Nastran software package (Fig. 7, 8) correctly reproduced both the general nature of deformation and the localization of the maximum stress zones. The calculated displacement at point A1 is 2.7 mm, which differed from the experimental value by approximately 12.9%. This difference is acceptable for brittle glass structures and is due to the idealization of boundary conditions, simplified contact modeling, as well as the absence of microdefects and residual stresses in the calculation model.

Unlike studies [3–5], in which the stress state of glass shells is mostly estimated only computationally, our work shows a real coincidence of the maximum stress zones with the actual fracture areas.

The results are consistent with the well-known studies on thin-walled spherical shells, which show that local application of load leads to a concentration of tensile stresses in the contact zone and can initiate a loss of the shell's bearing capacity. Similar patterns of the stressed-strained state of spherical shells under the action of axial and local loads are described in [22–24], in which the determining influence of the shell geometry and load application conditions on the nature of the stress distribution and the fracture mechanism is noted.

The advantage of this study compared to known work is the direct combination of experimental determination of the fracture mechanism with numerical prediction of the stressed-strained state. That allowed us to confirm that the zones of maximum tensile stresses, determined by the finite element method, coincide with the experimentally recorded areas of dome failure.

Thus, the devised experimental methodology and the constructed numerical model allowed for a comprehensive approach to the study on the mechanical behavior of the glass dome. The combination of laboratory tests with detailed finite element analysis allowed us to obtain reliable and reproducible data on the deformation characteristics and stress state of the shell. The proposed approach created a scientifically sound basis for further analysis of the results, verification of numerical models, and development of recommendations for the design of glass dome structures.

Our results have important applied significance, in particular for designing glass dome shells, which are considered to be promising structures for hermetic modules under extra-terrestrial conditions, in particular on Mars. The peculiarity of the results is the experimental confirmation of regularities in the formation of the stressed-strained state of the glass dome and the verification of the numerical model by the finite element method. That has made it possible to establish a correspondence between the predicted zones of maximum stresses and the actual zones of structural failure.

Limitations of our research are related to the use of monolithic glass, simplified loading scheme, and lack of consideration of temperature and long-term effects. Further development of the work should be directed to the study of multilayer glass domes, combined loads, and large-scale models close to actual operating conditions.

7. Conclusions

1. We have experimentally established that the glass dome operates mainly in a membrane stressed state until the moment of failure. The failure has a brittle, explosive nature,

and is initiated in the apex zone at loads of 1940–1960 kN/m² due to the concentration of tensile stresses. The maximum vertical displacement at point A1 was 3.1 mm; the similarity of the deformation curves confirmed the reproducibility of the results.

2. The numerical model, implemented by the finite element method, adequately reproduced the nature of the deformation and the localization of the zones of maximum stresses. The difference between the calculated (2.7 mm) and experimental (3.1 mm) displacement values was 12.9%, which indicates a satisfactory consistency of the results. The maximum tensile stresses of 53.8 MPa are greater than the standard resistance of glass, and the coincidence of the stress zones with the fracture areas confirms the reliability of the numerical approach.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors used artificial intelligence technologies within the permissible framework to provide their own verified data, which is described in the research methodology section. ChatGPT (OpenAI), GPT-5.2 model.

The AI tool was used during the preparation of text formulations in the sections “Introduction”, “Analysis of literary data and statement of the problem”, “Discussion of the regularities of the stressed-strained state of a glass dome”.

Image creation, linguistic and stylistic editing of the text, improvement of the structural logic of the presentation of the material.

AI was used only for text formations without the formation of results. Final editing was performed by the authors with full control over the content.

The use of artificial intelligence tools did not affect the obtained scientific results. AI was used exclusively as an auxiliary tool to improve the quality of the presentation of the material.

Authors' contributions

Bogdan Demchyna: Conceptualization, Supervision; **Roman Tkach:** Methodology, Formal analysis; **Roman Kotselko:** Investigation, Resources; **Khrystyna Demchyna:** Writing – original draft, Visualization.

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