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RESEARCH ARTICLE

DEFECTS AND ACCIDENTS OF THIN-WALLED SLOPING REINFORCED CONCRETE SHELLS

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Abstract. *Safety requirements for building structures aim to prevent accidents and collapses of buildings or their individual elements that may endanger human life, harm the environment, or trigger other emergencies. Although it is impossible to completely eliminate accidents, it is crucial to ensure that when design loads are exceeded, failures remain localized and do not grow into progressive or cascading collapses. When analyzing the causes of structural failures, attention must be given to errors made during the design, construction, and operational stages. Notable example of a failure caused by design shortcomings is the collapse of the roof of the Yasenevo water park in Moscow, RF. Article presents verification calculations of the reinforced-concrete shell that revealed insufficient strength, stiffness, and stability. Primary cause was an unsuccessful design choice - selecting a shell geometry with excessively flat areas near the support contour, which significantly reduced its load-bearing capacity. Special emphasis is placed on the survivability of buildings and structures, including their ability to maintain structural integrity under unexpected or extreme loads. Paper examines factors that contributed to the shell collapse: total deflections, excessive flatness, inadequate rigidity, actual operational loads, and real physical-mechanical properties of materials. Recommendations are provided for the design of shallow reinforced-concrete shells, highlighting critical aspects that require the designer's attention to avoid similar failures. Modern calculation program STARK_ES3.1 is used for analyzing shallow reinforced-concrete surfaces, with geometric parameters and material properties presented in detail. Expanded literature review is included, focusing on creep, long-term performance, and durability of shallow reinforced-concrete shells.*

Keywords: *collapse, accident, reliability, shell, safety, load, survivability, operation***.**

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ҒЫЛЫМИ МАҚАЛА

ЖҰҚА ҚАБЫРҒАЛЫ ДОҒАЛ ТЕМІРБЕТОН ҚАБЫҚШАЛАРДЫҢ АҚАУЛАРЫ МЕН АПАТТАРЫ

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Аңдатпа. *Құрылыс конструкцияларының қауіпсіздігін қамтамасыз етуге қойылатын талаптар адамдардың өмірі мен денсаулығына қауіп төндіретін, қоршаған ортаға зиян келтіретін немесе өзге де төтенше жағдайларды тудыруы мүмкін ғимараттардың немесе олардың жекелеген элементтерінің апаттары мен құлауын болдырмауға бағытталған. Апаттардың пайда болу мүмкіндігін толығымен жоққа шығару мүмкін емес, бірақ жүктемелер жойылудың жобалық мәндерінен тыс болған кезде прогрессивті, тізбекті емес, жергілікті болуын қамтамасыз ету қажет. Апаттардың ықтимал себептерін талдау кезінде ғимараттарды жобалау, салу және пайдалану кезеңдерінде жіберілген қателіктерді ескеру қажет. Жобалық қателікке байланысты апаттың нақты мысалы – Ресей Федерациясы, Мәскеу қаласы, Ясеневтегі аквапарк жабынының құлауы. Мақалада құрылымның темірбетон қабығының тексеру есептеулері қарастырылады, бұл оның беріктігі, тұрақтылығы мен қаттылығының жеткіліксіздігін анықтады. Негізгі себеп сәтсіз жобалық шешім болды – тірек контурының жанында тым доғал аймақтары бар қабық пішінін таңдау. Ғимараттың немесе үймереттің ұзақ мерзімділігіне ерекше назар аударылады. Сондай-ақ, жұмыста қабықшаның апат себептері, олардың жалпы ауытқулары, шамадан тыс дөңестігі, құрылымның қатаңдығы, нақты жүктемелердің әсері және пайдалану кезінде материалдардың нақты физикалық және механикалық сипаттамалары қарастырылады. Доғал темірбетон қабықшаларын жобалауға арналған ұсыныстар берілген және конструктор нені ескеруі керек. Доғал темірбетон жабындарын есептеу үшін STARK_ES 3.1 заманауи есептеу бағдарламасы қолданылды. Есептеу үшін қабықшаның геометриялық өлшемдері мен материалдарының физикалық және механикалық қасиеттері сипатталады. Доғал темірбетон жабындарының жылжығыштығы мен беріктігі туралы кеңейтілген әдеби шолу жасалды.*

Түйін сөздер: *құлау, апат, сенімділік, қабық, қауіпсіздік, жүктеме, өміршеңдік, пайдалану*.

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НАУЧНАЯ СТАТЬЯ

ДЕФЕКТЫ И АВАРИИ ТОНКОСТЕННЫХ ПОЛОГИХ ЖЕЛЕЗОБЕТОННЫХ ОБОЛОЧЕК

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Аннотация. *Требования к обеспечению безопасности строительных конструкций направлены на предотвращение аварий и обрушений зданий или их отдельных элементов, которые могут представлять угрозу жизни и здоровью людей, нанести ущерб окружающей среде либо спровоцировать иные чрезвычайные ситуации. Полностью исключить возможность возникновения аварий невозможно, однако необходимо стремиться к тому, чтобы при выходе нагрузок за пределы проектных значений разрушения были локальными, а не носили прогрессирующий, цепной характер. При анализе возможных причин аварий важно учитывать ошибки, допускаемые на этапах проектирования, строительства и эксплуатации зданий. Показательный пример аварии из-за проектной ошибки – обрушение покрытия аквапарка в Ясеневе город Москва Российская Федерация. В статье рассмотрены проверочные расчёты железобетонной оболочки конструкции, которые выявили её недостаточную прочность, устойчивость и жёсткость. Основной причиной стало неудачное проектное решение – выбор формы оболочки с чрезмерно пологими участками вблизи опорного контура. Особенно уделяется внимание на живучесть здания или сооружения. Также в работе рассматриваются причины обрушения оболочки, их суммарные прогибы, чрезмерная пологость, жесткость конструкции, действия фактических нагрузок и фактических физико-механических характеристик материалов при эксплуатации. Даются рекомендации для проектирования пологих железобетонных оболочек и на что должны обратить внимания конструктора. Используется современная расчетная программа STARK_ES 3.1. для расчета пологих железобетонных покрытий. Для расчета описывается геометрические размеры и физико-механические свойства материалов оболочки. Проведен расширенный литературный обзор по ползучести и долговечности пологих железобетонных покрытий.*

Ключевые слова: *обрушение, авария, надежность, оболочка, безопасность, нагрузка, живучесть, эксплуатация*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

The authors declare that no generative artificial intelligence technologies or AI-based tools were used in the preparation of this article.

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ деп мәлімдейді.

Авторлар мақаланы дайындау барысында генеративті жасанды интеллект технологиялары мен жасанды интеллектке негізделген технологияларды пайдаланбағанын мәлімдейді.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы заявляют, что конфликта интересов нет.

Авторы заявляют о том, что при подготовке статьи не использовались технологии генеративного искусственного интеллекта и технологии, основанные на искусственном интеллекте.

1 INTRODUCTION

According to foreign scientists Fani Derveni, thin-walled reinforced concrete structures with a slight slope (RC) are an important and in-demand construction structure for 2022-2025: they are used in large-span roofs, dome structures, hangars and sports facilities, as well as in other projects requiring a combination of lightness, aesthetics and economy of materials. However, along with the advantages of this design, there are significant risks of design errors, defects, and accidents due to the shell's specific operating characteristics: its thin thickness, significant geometric disturbances, wind and snow loads, as well as operational wear and tear and environmental impacts.

According to Professor T.T. Mussabayev, defect verification is related to the fact that the structural efficiency of shells is achieved by minimizing thickness and material, which makes them particularly sensitive to defects (geometric, material and installation) and sudden damage (for example, local deflection, uncontrolled deformation and destruction of the shell).

By their very nature, shells are sensitive to irregularities in shape, roof slope, and installation unevenness. For example, studies show that even small geometric distortions significantly reduce the critical load of shells (**Fani Derveni et al., 2024**).

In reinforced concrete shells, processes such as concrete creep, shrinkage, reinforcement corrosion, and fatigue cracks are significant, as they can gradually reduce the strength, rigidity, and stability of the structure. For example, (**Mussabayev et al., 2023**) consider concrete creep in shells to be the important factor in reducing the stability of the structure.

Inaccuracies in the shell's shape, imprecise reinforcement, weld defects, and unaccounted for or atypical loads (wind, snow, dynamics) result in the shell operating not only in membrane mode but also experiencing significant bending and shear forces. For example, (**Cardoso et al., 2024**) showed that uneven and asymmetric loading on a thin concrete shell leads to bending moments and exceeding the concrete's ultimate stress.

Typical failure scenarios for shells include buckling, localized failure of concrete and/or reinforcement, sudden shape changes (e.g., due to support or settlement), accumulation of deformations, and subsequent collapse. A study by (**Iskhakov, Ribakov, 2014**) emphasizes that in large-span reinforced concrete shells, the frequency of failures is due to the failure of the design to account for long-term creep and shape changes.

One of the distinctive features of thin-walled shells is their high sensitivity to geometric deviations (initial misalignment, less-than-ideal curvature, installation errors). Such defects can significantly reduce the critical buckling load of a structure. For example, the authors (**Anais Abramian et al., 2020**) indicate that even virtually imperceptible defects can lead to a reduction in the critical collapse load of cylindrical shells. Thus, buckling (including local or global) is an important mechanism for shell failures.

Thin-walled structures, especially those with large spans, are often subject to increased loads: snow loads, wind loads, dynamic loads (e.g., vibrations), unaccounted for bearing settlements, and installation loads. If the structure is poorly designed for these conditions, or installation/operating defects/costs are not accounted for Eads to failure. For example, it has been reported that some thin-walled dome structures have been subjected to significant hurricane or tornado impacts and withstood them, but it has also been noted that unaccounted for loads can be critical (**Andrew South, Chris Zweifel, 2021**).

Shells require high precision in formwork, reinforcement, and connections. Errors in these stages (incomplete reinforcement, weak joints, improper formwork/formwork installation) educe the safety factor and stability. Even if operational loads are calculated, installation defects can lead to premature failure.

Often, the cause of a failure is not a single factor, but a combination of them: a geometric defect + a material with a loss of strength + a sudden load (e.g., wind + snow) → the combined effect leads to failure. Predicting such situations is difficult, as the effects uncontrollably reinforce each other.

The problem of ensuring the reliable and safe operation of newly constructed, operated, and reconstructed facilities for various purposes is becoming increasingly important in the face of increasing natural and man-made impacts.

Emmanuel Virot notes that in emergency situations, two modes of structural system failure are distinguished: avalanche-like, i.e. when failure of even one element leads to the destruction of the entire system or most of it, and localized, i.e. failure of one or more elements occurs in a limited area.

Although GOST 27751-88 «Reliability of Building Structures and Foundations» (**GOST 27751-88, 1988**) states that structural calculations should consider the emergency design situation arising immediately after the failure of any structural element, it does not define any failure modes or provide specific recommendations for protecting structures from progressive collapse.

The building code DIN 1055-100 “Loads and Actions” and Eurocode (**ENV 1991-2-7. EUROCODE 1, 1991**) specify measures that must be included in the design to prevent emergency situations. These include:

- selecting a structural system characterized by low sensitivity to the aforementioned hazard;
- selecting a structural system in which the failure of an individual element or adjacent parts, or localized damage, does not lead to a loss of the load-bearing capacity of the entire structure;
- using structural systems whose loss of load-bearing capacity is accompanied by warning signs.

These requirements must be met through the selection of suitable building materials, appropriate calculations and design, and the selection of control methods during the development of design documentation, construction, and operation of the structure (**ENV 1991-2-7. EUROCODE 1, 1991**).

To reduce the incidence of accidents or damage when they occur, an important task is to develop approaches to structural design that ensure maximum survivability of the building or structure.

Klinkel S. He says that survivability is the ability of a system to maintain its load-bearing capacity in the event of failure of one or more structural elements. The increased survivability is facilitated by the multiple static uncertainty of the building (structure) and the possibility of spatial redistribution of forces within its structural system.

2 LITERATURE REVIEW

Anais Abramian's research has studied carbonaceous concrete, and it is known that the tensile strength of carbon is significantly higher than that of steel, which makes it possible to manufacture filigree parts and further gives impetus to the development of new construction methods. This study focuses on the development of new evaluation methods for the analysis of thin carbon fiber concrete (CRC) structures. CRC allows you to explore delicate components and the latest construction techniques due to its high tensile strength. In the work of Iskhakov I. The author expands the analysis of CRC shells based on existing research. The internal structure of CRC specimens was investigated using microtomography. Rovings within the specimens were segmented from 3D tomographic reconstructions using a 3D convolutional neural network with improved 3D data augmentation strategies and further analyzed using image-based methods. The main contribution is the assessment of fabrication accuracy and modeling of the structure's behavior by measuring the position of the carbon mesh within the concrete. Based on the segmentations, surface point clouds were obtained, which were then integrated into a multiscale structure using a parameterized representative volume element that captures the characteristic properties of the textile reinforcement. The procedure is presented using an example covering all necessary design steps from computed tomography to multiscale analysis. The framework enables efficient evaluation of new construction methods and analysis of the linear elastic behavior of CRC shells (**Wagner et al., 2023**).

According to the expert Mester L., lightweight supports have a number of advantages, including low weight, less need for materials and lower construction cost. In the last few decades, they have been widely used in the design of urban viaducts, railway bridges and bridges for expressways, demonstrating excellent development dynamics and high practical value. Lightweight supports are becoming commonplace on urban overpasses and bridge structures in 2022-2025. This type of support is widely used in structural engineering. A thin-walled composite concrete support (TSRCP), as a typical lightweight support, exhibits superior mechanical properties compared to a conventional reinforced concrete support due to the reinforcement of the H-section steel. In the research of H.Chen says that the complex process of calculating the initial equation can be simplified, which not only provides a convenient and useful way to design and manufacture such components, but can also serve as a guide for verifying practical applications for engineering purposes (**Chen et al., 2022**).

The studies by Skadiš U and Kuevskis K. examined thin-walled sandwich walls (SW) made of steel-fiber reinforced concrete (SFRC) without traditional reinforcement. Researchers Vulans A and Brencis R. have shown that PBBs with thin partitions can be used as load-bearing structures in low-rise buildings, reducing concrete consumption by 2-5 times compared with traditional reinforced concrete PBBs. K.Kuevskis' research focuses on relatively warm climates and studies thin-walled SBS with shear elements to achieve a certain level of composite performance. Numerical analyses of structural, thermal, and acoustic insulation properties were also performed (**Skadiš et al., 2023**).

In traditional construction using composite steel, solid, weakly structured elements with constant external and internal geometry are typically used. It is not uncommon to encounter areas of structural elements where concrete and reinforcement are underutilized because construction methods are not adapted to the material properties and potential of the composite. Small or even unstressed areas in flexural elements are well known. This drawback, which also exists in construction using carbon-reinforced concrete (CRC), was the impetus for the joint research project CRC/TRR 280 «Design Strategies for Minimal Material Consumption of Carbon-Reinforced Concrete Structures - Principles for a New Construction Approach», funded by the German Research Foundation (DFG). The overall objective is to develop a universal design strategy for carbon-reinforced concrete structures that takes into account the advantages of this composite while strictly considering the need for material suitability. In work I.Vakaliuk presents the main implemented approaches to analysis. I.Vakaliuk describes the basic workflow, the software used, and the material models, as well as their calibration using textile-reinforced concrete (TRC) samples. (**Vakaliuk et al., 2024**).

A common structural defect in tunnels during operation is cracking of the concrete lining. Insufficient lining thickness is one of the main causes of cracking. In the research of Liu J. and Zhang X. The cracking of standard concrete samples and the destruction of tunnel structures caused by insufficient lining thickness were studied using the adhesion zone model (CZM). First, zero-thickness cohesive elements were inserted between the solid elements of a standard concrete specimen model, and crack propagation in different concrete grades was compared. Based on the above-mentioned data, a three-dimensional numerical model of the tunnel was created during operation. The mechanism and characteristics of crack propagation with different lining thicknesses were examined. Furthermore, crack statistics were compiled to quantitatively analyze crack development patterns in the lining. The results of K.Wang shows that CZM adequately models the behavior of concrete during fracture. As the concrete strength class increases, the number of damaged cohesive elements and the crack area increase. Insufficient lining thickness alters the stress distribution characteristics within the lining, reduces the overall safety of the lining structure, and leads to more prone cracking in the affected area. If the lining thickness is insufficient, the surrounding rock is less exposed to the lining than if the entire lining thickness is filled with surrounding rock (**Liu et al., 2021**).

Nonlinear analysis procedures used in the performance-based design/evaluation of structural systems with reinforced concrete walls are significantly improved by the introduction of a robust modeling approach capable of accurately modeling the nonlinear response characteristics of both planar and non-planar walls at both global (force-displacement, moment-rotation, torque-torsion) and local (e.g., strains, shear strains, bending strains) response levels under combined and multidirectional loading conditions. Nonlinear response history analysis is a widely used analysis method for assessing the seismic performance of existing structures or for performance-based design of special structures such as high-rise buildings (**Tura et al., 2025**).

Modular wall panels are increasingly being used in construction. New dual-layer composite wall panel (DSC) technology uses clinch joints to join two rolled open-section profiles into a hollow steel shell, which is then filled with lightweight aerated concrete. This can provide a fire-resistant DSC solution for use in commercial and high-rise buildings. One important material parameter for application is the panel's resistance to wind loads. This study represents the first fundamental analysis of the structural behavior of the new DSC wall panel under wind loads. This includes three- and four-point bending tests combined with in-situ chamber analysis, as well as joint strength and concrete performance analysis. The experimental results confirm for the first time that the aerated concrete core of the DSC panel has only a minor effect on the wall's flexural performance. Most of the bending loads are absorbed by the tensile and compressive deformation of the steel outer shell and the shear deformation near the clinch joint. Thus, failure under maximum load occurs not due to cracking of the concrete, but due to buckling of the steel sheet or a mixed type of failure, combining buckling of the steel and opening of the seams (**Weiss et al., 2025**).

With the development of industrialization and urbanization, the use of thin-walled steel tubes in concrete-filled steel tube columns has become important in the design of low-rise buildings. These columns are lightweight, require less welding, and are cost-effective. However, their load-bearing capacity is relatively low, and localized buckling often occurs in thin-walled steel tubes. To address the problem of localized buckling of thin-walled concrete tube columns, a helical stiffener design was proposed. Axial compression tests were conducted on five cross-sections of square concrete tube column specimens. The study revealed that, compared to conventional concrete tube columns, the axial compressive load-bearing capacity and deformation capacity of concrete tube columns restrained by helical stiffeners increased by 18.5% and 7.7%, respectively. The helical stiffeners effectively increased the buckling resistance of thin-walled concrete tube components. The failure mode of this new component was characterized by diagonal cracks in the concrete aligned with the direction of the helical stiffeners, and buckling of the steel tube walls was concentrated between the helical stiffeners. Based on the experiments, an analysis of the buckling characteristics of thin-walled steel tubes restrained by helical stiffeners was conducted and incorporated into the load-bearing capacity calculation. Testing, modeling, and theoretical calculations showed that the error in determining the load-bearing capacity of composite columns for each sample did not exceed 10%. Ultimately, a formula was proposed for determining the critical load-bearing capacity of steel pipes with spiral stiffeners upon buckling (**Tian et al., 2024**).

Professor A.V. Perelmuter, in his monograph (**Perelmuter et al., 2000**), asserts that an accident is always a specialist's error, regardless of whether it is caused by underestimating the external load or by insufficient load-bearing capacity that developed during the construction and operation of the facility (during surveys, design, construction, operation, and repair). He provides a graphical representation of the average causes of failures of steel structures (Fig. 1).

These causes can easily be attributed to reinforced concrete structures, with a slightly increased proportion of low-quality materials due to manufacturing and installation defects (**Seiitkassymuly et al., 2025; Moldamuratov et al., 2025; Aldakhov et al., 2025; Ilyassova et al., 2025**).

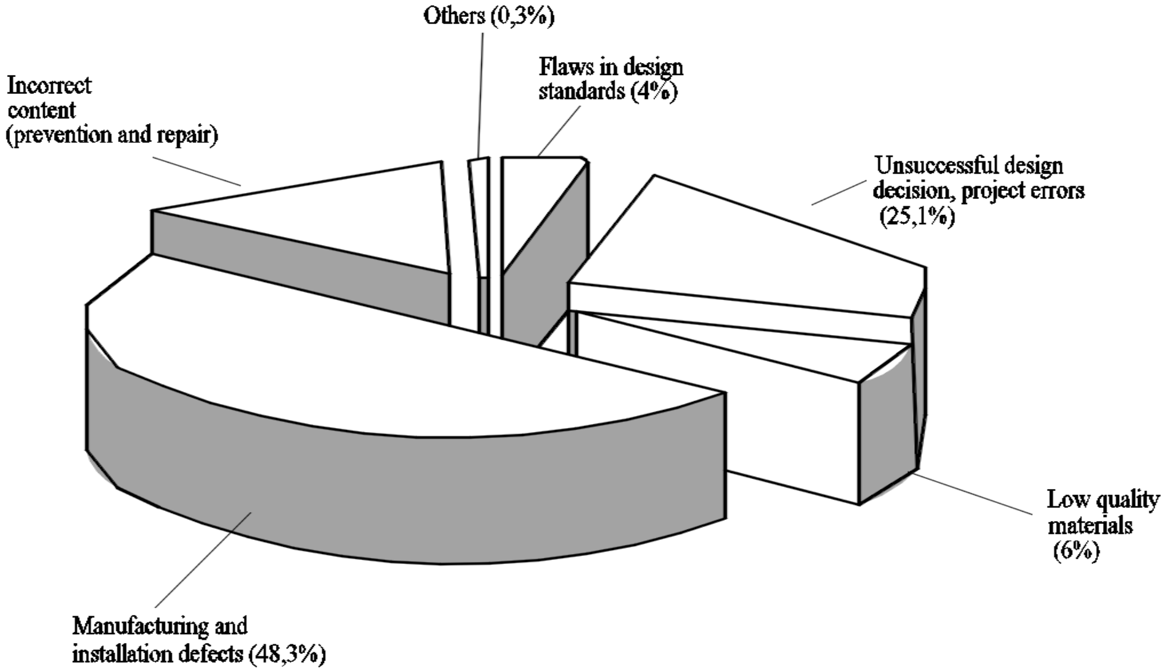

Figure 1 - Average causes of accidents

The likelihood of serious design errors depends largely on the unjustified choice of the structural design, calculation scheme, and adopted calculation methods.

One typical example of an emergency resulting from design errors is the collapse of the water park's roof shell in *Yasenev, Moscow, Russian Federation.*

3 MATERIALS AND METHODS

The water park's roof is a gently sloping ribbed reinforced concrete shell (Figure 2), in plan, it is a circular sector with a central angle of 105°, the radial sides of the sector are 70 m long, and the curved side is approximately 130 m long. A I200 x 500(h) mm curb is installed along the shell's perimeter. The rib height, including the shell, is 400 mm, and the ribs on the lower surface form a lattice with triangular cells. The rib thickness is 250 mm near the perimeter and 120 mm over the rest of the shell's surface. The shell thickness between the ribs in the central zone of the roof is 70 mm, while in areas adjacent to the curb, the shell thickness is increased to 200 mm. The roof is supported by columns (Ǿ426x9 steel pipes with a height of 7 to 18 m) and by hinged supports on the foundation. The structure's supports are made of tubular steel columns measuring Ǿ426x9. A bracing system is installed between the columns in the planes of all three facades.

The roof collapse occurred on February 14, 2004, resulting in numerous casualties. To determine the cause of the disaster, a series of verification calculations of the roof structure were performed at the Research Institute of Reinforced Concrete (RIRC) on behalf of the state commission.

The roof structure of the water park was calculated using the finite element method and the STARK_ES 3.1 software package. The STARK_ES 3.1 software package is designed to calculate the structures of buildings and structures for strength, stability and vibrations based on the finite element method program. The STARK_ES 3.1 software package is used for numerical modeling and calculation of structures of buildings and structures under various static and dynamic force and kinematic influences based on the finite element method.

The roof's supporting structure was calculated taking into account the structure's own weight, the roof's weight, and snow loads.

The following calculations were performed:

- determination of the deformation state of the shell after unscrewing;
- determination of the total deflection under standard loads, taking into account their long-term action;
- calculation of the structural stability under design loads adopted in accordance with current standards and a reduced concrete deformation modulus (as recommended in the "Guidelines" using a coefficient accounting for short-term concrete creep, $j_{b1} = 0.85$, and various j_{b2} coefficients accounting for long-term concrete creep.
- calculation of the structural stability under the design loads adopted during the design;
- Calculation of stability under constant and long-term loads (30% of the total snow load, according to the standards in effect at the time of the shell design);
- calculation of the bearing capacity of the contour element under the design loads under conditions of column failure along the 9g axis;
- calculation of the stability of the roof structures under actual loads on the shell, taking into account the physical and mechanical properties of the concrete, adopted based on strength testing data.

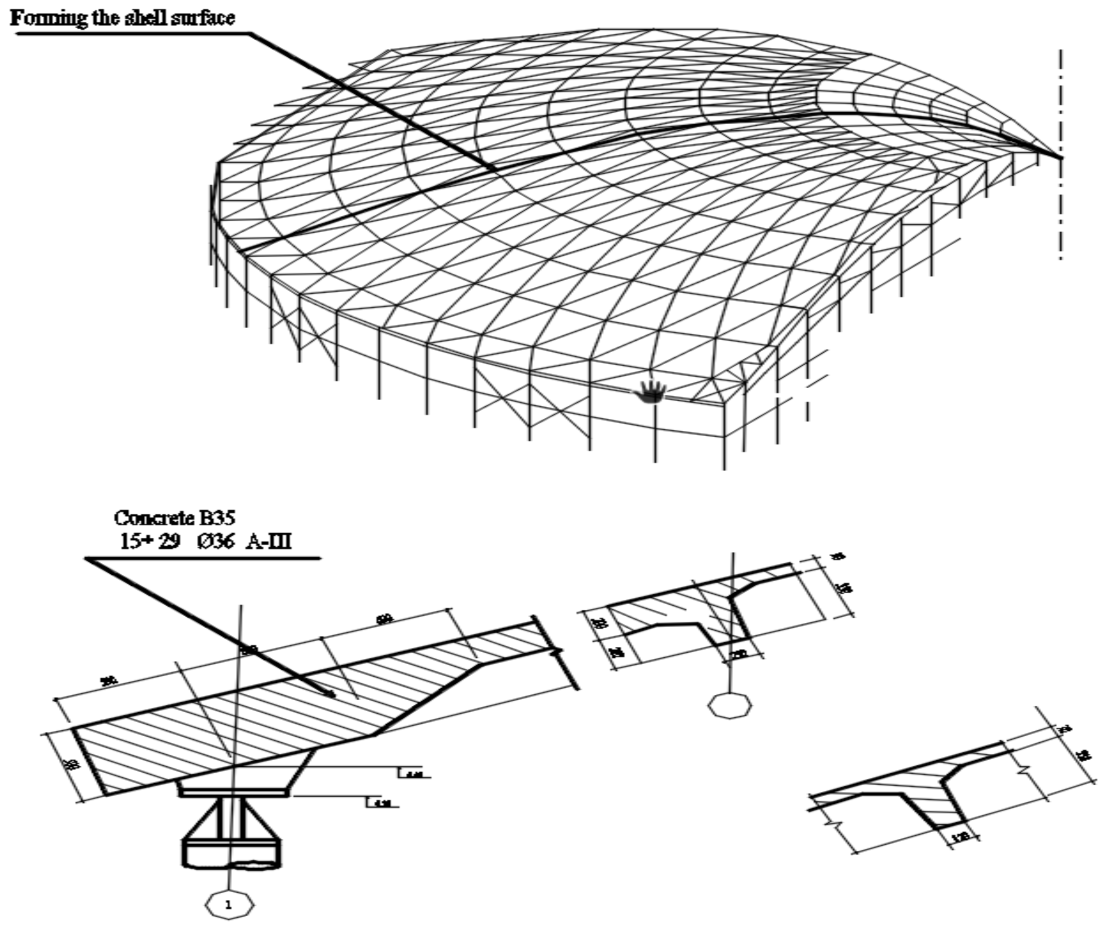

Figure 2 - General view of the water park roof and the main sections of the covering elements in the support contour area (left) and in the middle part of the span (right)

4 RESULTS AND DISCUSSION

The calculations revealed the following:

1. Initial Deflection:

The shell deflection due to its own weight load along the axis of symmetry was 114.7 mm, which correlates well with measured values during the shell's unwrapping. This confirms the accuracy of the applied modeling techniques for self-weight effects.

2. Total Deflection and Instability under Load:

The total deflection under full loading (including long-term load effects), calculated linearly, reached 244.7 mm, a value close to the typical sag of large-span lifting systems. However, nonlinear analysis revealed loss of stability at only 70% of the design load, with deflections exceeding 600 mm (Fig. 3). Alternating bending moments in annular ribs near the contour (Fig. 4) indicate the formation of indentations – a sign of local buckling typical in thin shell structures. This behavior suggests critical sensitivity to geometric and loading imperfections.

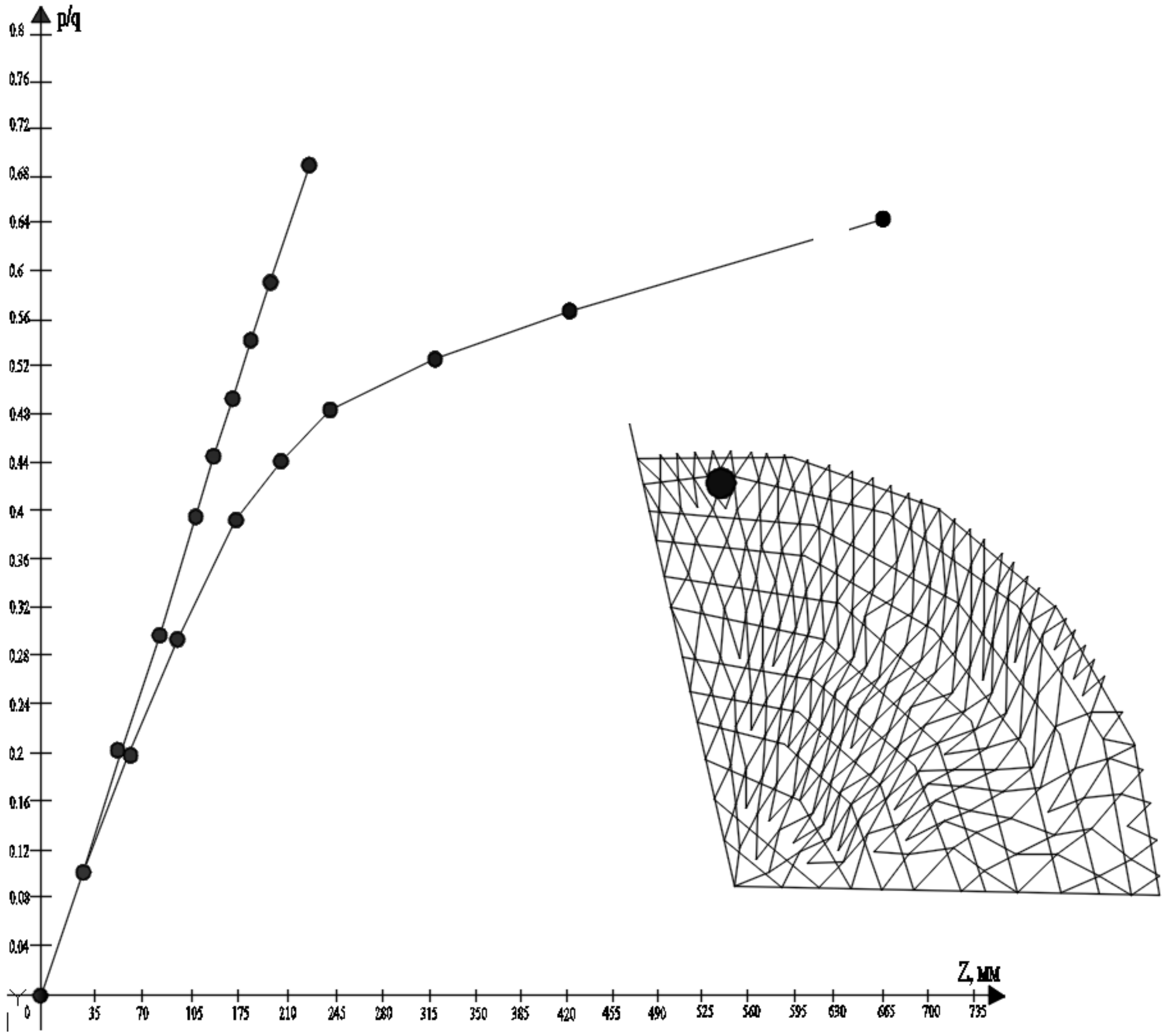

Figure 3 - Calculated values of deflection depending on the load intensity P (relative to the value of the total calculated load q) in a linear calculation (1) and in a calculation taking into account geometric nonlinearity (2)

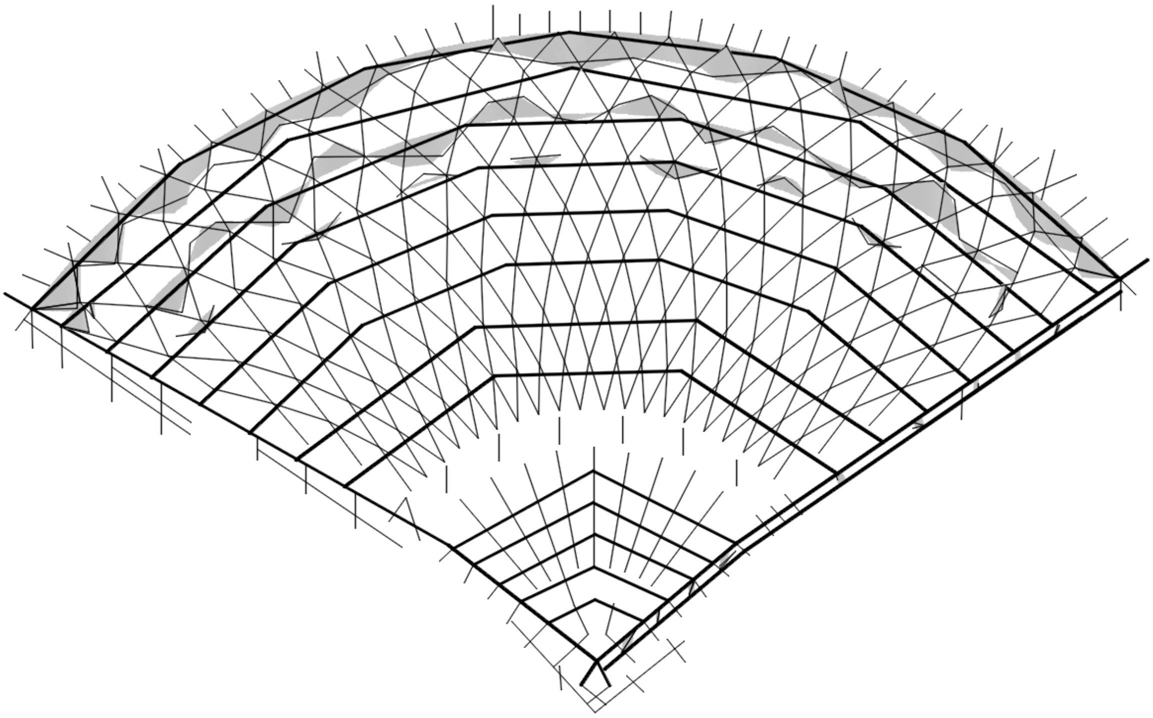

Figure 4 - Bending moment diagram in the shell ribs in the calculation taking into account geometric nonlinearity

3. Insufficient Rigidity Due to Surface Geometry:

The analysis showed that the shallow-sloping geometry near the contour, combined with the current structural design, does not provide sufficient stiffness (Fig. 2). This outcome aligns with previous research on shallow RC shells, where excessive flatness leads to instability under relatively low loads.

4. Stability Margin and Collapse Sequence:

The shell loses stability at 60–68% of the normative load when long-term concrete creep is included. Further refined calculations, incorporating actual material properties and real loading conditions, indicate loss of stability at 77% of the design load. In all scenarios, the failure is initiated by alternating local dents (Fig. 5), consistent with progressive shell instability patterns reported in recent studies of RC dome structures.

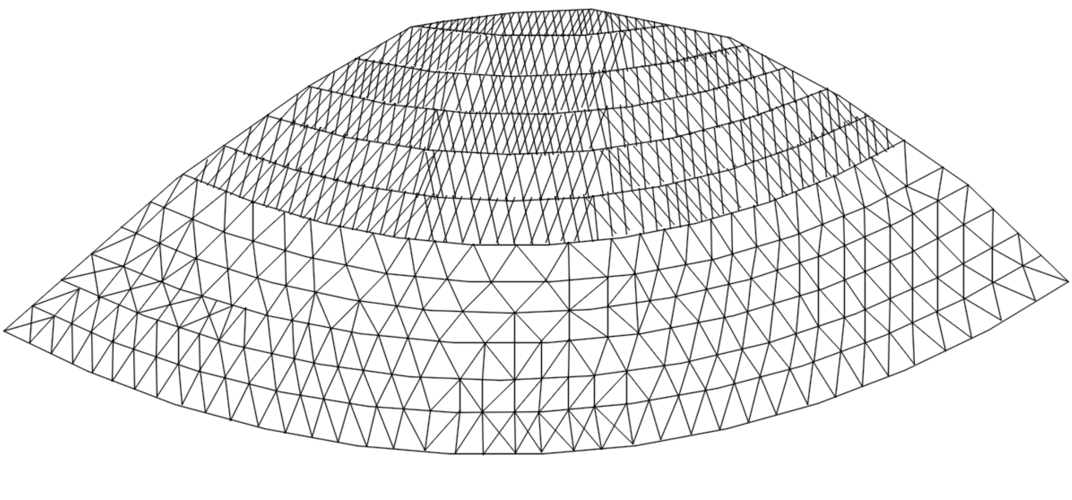

Figure 5 - General view of the 1st form of loss of stability of the roof shell

5. Collapse Sensitivity to Support Failure:

The failure of a single column causes a loss of support in the contour element, which could trigger a global collapse of the entire roof. This highlights the lack of redundancy and the critical need for robust detailing at support zones.

5 CONCLUSIONS

1. It is necessary to select structural designs or the shape of the roof surface such that the inability of any element to bear the load from a prohibited impact does not lead to the destruction of the entire structure or a significant portion thereof.

2. Work should be continued on the development of calculation tools and programs for the analysis of nonlinear deformation, cracking, and failure of reinforced concrete statically indeterminate structural systems upon the sudden disconnection of individual elements (nodes, connections), taking into account the history of their loading, in order to create structures protected from progressive failure.

3. For particularly complex and critical structural systems (large-span structures, high-rise buildings, etc.), in order to increase the level of safety, it is necessary to conduct structural testing during the design process using physical models and monitor the main load-bearing structures during construction and operation of the buildings.

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