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NUMERICAL STUDIES OF THE PERFORMANCE OF REINFORCEDCONCRETE ARCHES UNDER THE ACTION OF STATIC SHORT-TERM LOADS

Bohdan KARAVAN[1], Viktor KARAVAN[2], Serhii FILIPCHUK[3]

[1,2,3] The National University of Water and Environmental Engineering
11 Soborna St., Rivne, Ukraine, 33028

[1] b.v.karavan@nuwm.edu.ua, https://orcid.org/0000-0002-0499-7544
[2] v.v.karavan@nuwm.edu.ua, https://orcid.org/0000-0002-8261-692X
[3] s.v.filipchuk@nuwm.edu.ua, https://orcid.org/0000-0002-4464-4620

Bohdan KARAVAN
senior lecturer, Department of Industrial, Civil Engineering and Engineering Structures,
Doctor of Philosophy (Ph.D.)

Viktor KARAVAN
associate Professor, Department of Industrial, Civil Engineering and Engineering Structures,
Cand. Sc.

Serhii FILIPCHUK
associate Professor, Head of Department of Industrial, Civil Engineering and Engineering Structures,
Dr. Sc.

Annotation. The article describes the methodology for experimental studies of an arch made of high-strength rapid-hardening concrete, presents the results of the studies in tabular form, and describes the mechanical characteristics of the materials used in the manufacture of experimental arch specimens. The process of manufacturing experimental specimens from high-strength rapid-hardening concrete is briefly described. Drawings of the installation on which the stress-strain state of reinforced concrete double-hinged arches under the action of static single short-term loading was studied are also presented. Drawings of deformed and/or destroyed experimental specimens are demonstrated.

Currently, there is a need for the fastest possible construction rates for various purposes, which can be achieved by introducing high-strength rapid-hardening concrete into the technological process, which allows you to significantly increase the construction rate and, accordingly, reduce the construction time of buildings and structures. The deformation patterns under short-term static loading of high-strength concrete have not been studied enough to date, which complicates the calculations of reinforced concrete structures made of such concretes. This article is devoted to solving these problems.

There is a need to study the stress-strain state of reinforced concrete arches made of high-strength concrete under the action of static single and repeated loads of various levels and to in-depth determine the physical, mechanical and deformation characteristics of high-strength concrete. This will allow for a more accurate assessment of the stress-strain state of elements of reinforced concrete structures made of such concretes, increase the reliability of design
and obtain a significant economic effect in the construction of buildings and structures, which is an urgent task today.

Keywords: research; experiment; arch; concrete; testing; calculation.

INTRODUCTION

Reinforced concrete arch structures are widely used in industrial, civil construction, as well as in the construction of special buildings and structures [1, 2, 3, 4, 5]. Reinforced concrete arches are hinge less, single-, double-, triple-hinged. Most often in construction, double-hinged arches with and without a tightening are used, and in the case of large spans, triple-hinged. That is why double-hinged arches are more often used in the coverings of buildings and structures, the horizontal strut of which is perceived by a tightening or structural elements of the structure [6].

Currently, there is a need for the fastest possible pace of construction of structures for various purposes, which can be achieved by introducing high-strength quick-hardening concretes into the technological process, which make it possible to significantly increase the pace of construction and, accordingly, reduce the time for the construction of buildings and structures [7, 8, 9, 10, 11]. The deformation patterns under short-term static loading of high-strength concretes have not been studied sufficiently to date, which complicates the calculations of reinforced concrete structures from such concretes.

The finite element method (FEM) is a method developed for numerically solving complex problems in structural mechanics and other mathematical problems. In FEM, the structural model is written as a set of corresponding finite elements interconnected at discrete points, nodes. The structure is divided into elementary sections, which in turn are interconnected at separate points - nodes. The level of development of science and technology currently allows for the widespread use of software based on the finite element method, namely: LIRA-SAPR, ANSYS, Nastran, SCAD, Zebulon, etc.

ANALYSIS OF PREVIOUS RESEARCH

The dissertation work and scientific articles of Kyslyuk D. [12, 13, 14, 15, 16] are devoted to the study of the operation of double-hinged reinforced concrete arches with adjustment of forces under the action of repeated loads.

According to the results of experimental studies, the author concludes that repeated loads affect the stressed-deformed state of the arches, as a result of which the compliance of the tightening increases, that is, its rigidity decreases. It was established that the stabilization of the stressed-deformed state of the arch elements occurs depending on the level of repeated loads in the fifth - seventh cycles, and the additional loading of the arches during repeated loads above the operational level accelerates the stabilization of the stressed-deformed state. The formation and development of inclined cracks and the growth of plastic deformations in concrete cause a redistribution of internal forces in the upper belt of arches and tightening, while the increase in the strut decreases and the bending moment increases.

A. Pournaghshband, in his Ph.D. thesis in Engineering at the University of Warwick (Coventry, UK) [17], investigated two-hinged arches with the aim of finding the optimal moment-free design form. The finite element method implemented using GSA software was used to numerically analyze the three most common arch forms. The author recommends that, in order to maintain the structural efficiency of the arch, the ratio $l/h \approx 4$ should be chosen. The author also concluded that, provided that the arch has a constant cross-section and in the case of a constant radial load, the optimal form is a circular arch. In the case of a uniformly distributed load, the optimal form of the arch is a parabolic one, and for cases where only the load from its own weight acts, the optimal form is a contact arc arch

Y. Bouras [18], presented an analytical and numerical study in the ANSYS software package of the operation of arches made of silica-containing concrete, which are subjected to combined mechanical loads and the influence of elevated temperature. Thermal and mechanical properties of silica-containing concrete were taken from Eurocode, all parameters are summarized in the ANSYS table for an environment with a temperature of 22 ^{0}C and for temperature effects in the range from 100 ^{0}C to 1100 ^{0}C with a step of 100 ^{0}C.

According to the results of the experiments, the author concluded that the axial force and bending moment in the arch increase significantly with increasing temperature, and the arch deforms downward during heating. Thermal load significantly reduces the rigidity of the structure.

In [19, 20], the authors presented the results of experimental studies of the operation of three damaged and reinforced reinforced concrete arches under the action of asymmetric loading, as well as the operation of a reinforced concrete arch (RC) reinforced with UHPC in its various sections. One arch was strengthened with C50 (RC1-C50), and two arches with UHPC (RC2-UHPC, RC3-UHPC). The results of the studies showed that the cracking moment and the bearing capacity of composite arches reinforced with UHPC were increased by 185% and 186%, respectively, thereby confirming the significant effect of strengthening and strengthening the initial damaged arch. Under the condition of closing the cracks in the damaged arch, the stiffness of the composite arch reinforced with UHPC (RC2-UHPC) was improved by 58%. Unlike the arch reinforced with C50 (RC1-C50), in the arches reinforced with UHPC, no cracking and delamination was observed at the contact surface of the composite with concrete when subjected to loads. The bearing capacity of the arch reinforced with UHPC increased by 85.25% compared to the RC arch. Strengthening with UHPC according to different schemes and in different areas of the RC reinforced concrete arch prevents the formation of plastic hinges in its belt.

PURPOSE AND METHODS

The aim is to investigate the stress-strain state of two-hinged reinforced concrete arches made of high-strength concrete under the action of short-term single loads using modern, progressive calculation complexes. To achieve this goal, analytical studies were carried out based on the study of existing methods of stress-strain state of structures, analysis of open literature sources, and theoretical studies. A numerical experiment was also carried out to calculate experimental arches using the finite element method, and finally, a statistical analysis of the convergence of experimental and theoretical studies was performed.

RESULTS AND EXPLANATIONS

Reinforced concrete monolithic circular arches of both series had the following geometric parameters: nominal length – 216 cm; span *l* = 200 cm; nominal height – 52 cm; lifting boom *f* = 40 cm; ratio *f/l* = 1/5; radius of arch *R* = 145 cm; dimensions of the cross-section of the belt *h*×*b* = 14×10 cm (Fig. 1).

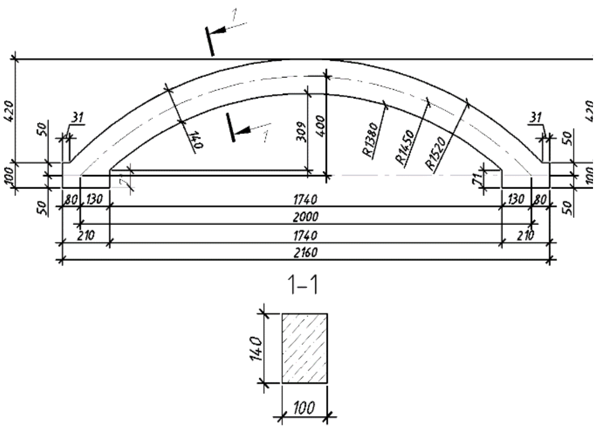

Fig. 1. Geometric dimensions of the reinforcedconcrete arch prototype.
Рис.1. Геометричні розміри дослідного зразка залізобетонної арки.

The reinforcement of the experimental arches was carried out using one knitted flat frame. Two rods Ø10 A500C (*As* + *As*/ = 1.57 cm^2) were used as working longitudinal reinforcement.

Fig. 2. General view of the manufactured frame.

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Рис.2. Загальний вигляд виготовленого каркаса.

A rod Ø10 A500C was used as a tightening. The reinforcement coefficient of the arch belt was ρ = 1.13%. (Fig. 2).

Based on the results of testing prismatic specimens from heavy fine-grained rapid-hardening concrete of class C80, a diagram of concrete deformation under a single short-term load to failure was constructed [21] (Fig. 3).

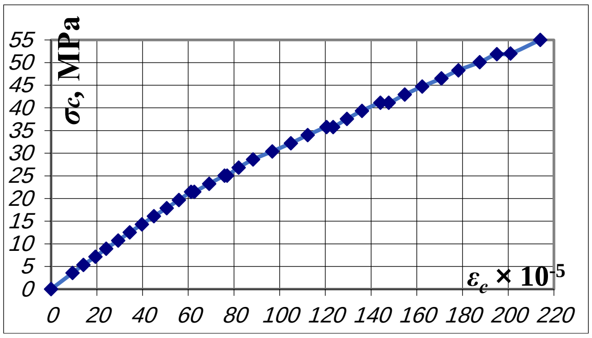

Fig. 3. Stress-strain diagrams of high-strength rapid-hardening concretes under axial compression at the age of 28 days.

Рис.3. Діаграми напруження-деформації високоміцних швидкотвердіючих бетонів при осьовому стиску у віці 28 днів.

To test the double-hinged reinforced concrete arches, a hydraulic press PG-200 was used, on the basis of which special equipment was mounted. The arch was tested under the action of a static step-increasing load until failure (Fig. 4).

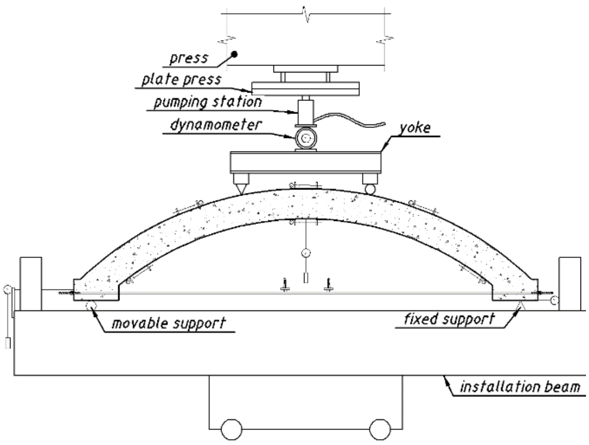

Fig. 4. Scheme of arch test with tightening.

Рис. 4. Схема випробування арки із затяжкою.

After processing the experimental data of the field tests, a numerical experiment was conducted. The essence of the experiment was to calculate the arch for a static one-time short-term load in the ANSYS.

The ANSYS software complex is currently one of the leaders in its field. It allows you to solve a wide range of tasks aimed at calculating and modeling nodes of structural elements, as well as modeling the flow of liquids and gases in the corresponding modules.

The advantage of using built-in geometry modeling tools is that they have additional capabilities for model parameterization and, in the event of changing any of the specified parameters, automatic modification of the entire model. Model parameterization also allows you to use the model shape optimization module or optimization by an objective function or criterion.

The calculation model was built in Autodesk Revit 2023 using a standard load-bearing structure template, which contains all the necessary parameters of reinforcement and concrete to create a structural diagram for further export to the ANSYS program (Fig. 5).

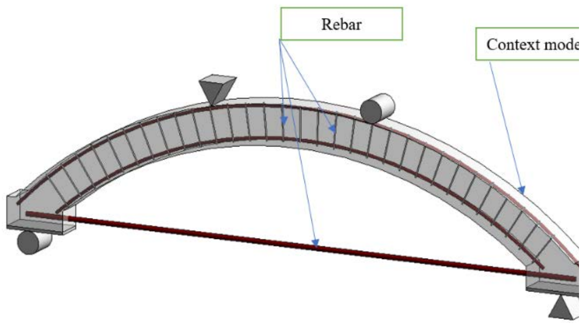

Fig. 5. General view of the design scheme of the arch in Autodesk Revit.

Рис. 5. Загальний вигляд розрахункової схеми арки в ПК Autodesk Revit..

The next stage is the generation of the model in the “Space Claim” graphical shell, which is an improved version of the “Workbench” module and allows you to combine the “dwg” and “acis(sat)” formats into a single ANSYS format calculation scheme and assign reinforcement properties to the lines and remove them from the main volume of concrete (Fig. 6).

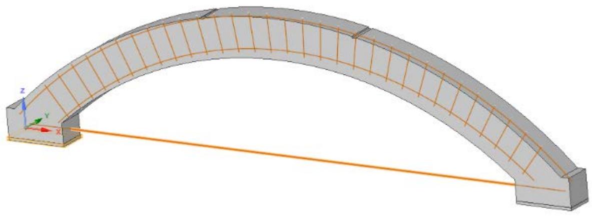

Fig. 6. Summary model of the structure in ANSYS “Space Claim”
Рис. 6. Зведена модель конструкції в ANSYS «Space Claim».

Concrete elements are modeled using the SOLID 65 finite element and reinforcement using Link 180. The SOLID 65 element is used for 3D modeling of bodies with or without strong bars (reinforcement).

The body can undergo tensile cracking or compression failure (loss of load-bearing capacity). The LINK180 finite element (beam element) consists of two nodes and has three degrees of freedom at each node. This type of FE is used for modeling uniaxial tension/compression.

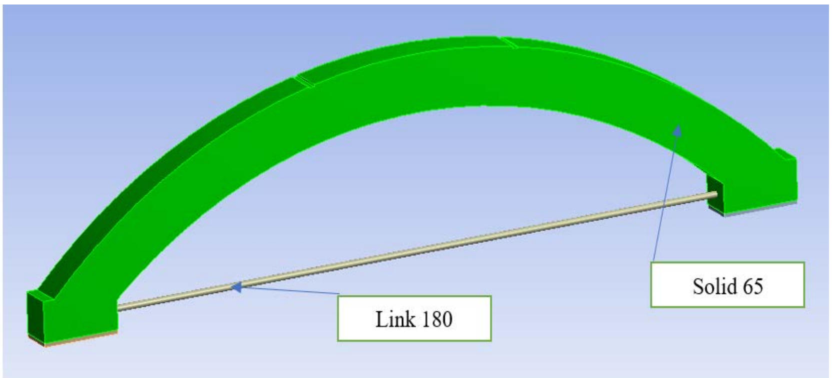

Fig. 7. Layout of SOLID 65 and Link 180 end elements.
Рис. 7. Схема розташування кінцевих елементів SOLID 65 та Link 180.

The calculation of the reinforced concrete arch was performed at a load of P = 10 kN, 50 kN, in accordance with the previously performed structural calculations in the LIRA-CAD software (Fig. 8…10).

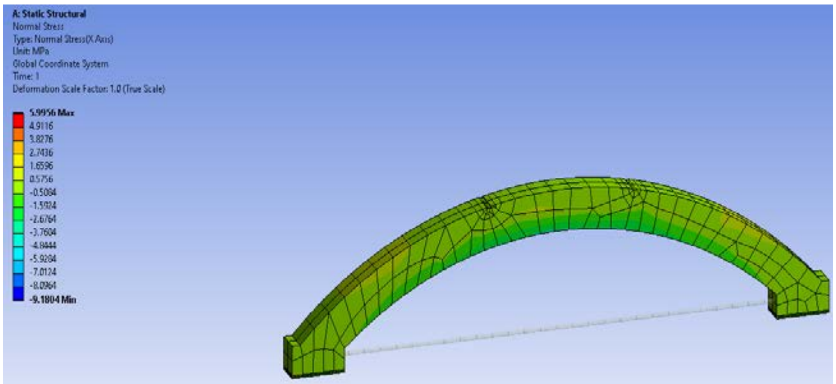

Fig. 8. Normal stresses (MPa) in the arch under load P=10 kN.
Рис. 8. Нормальні напруження (МПа) в арці при навантаженні P=10 кН.

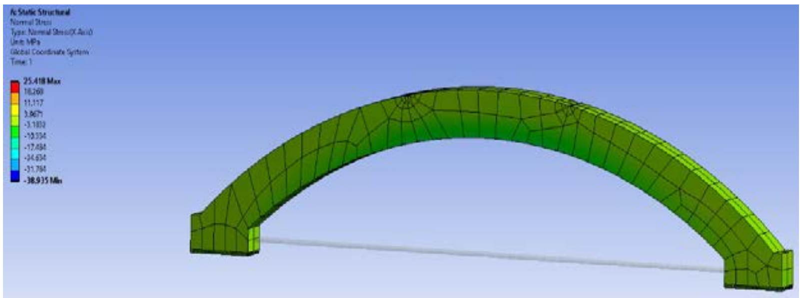

Fig. 9. Normal stresses (MPa) in the arch under load P=50 kN.
Рис. 9. Нормальні напруження (МПа) в арці при навантаженні P=50 кН.

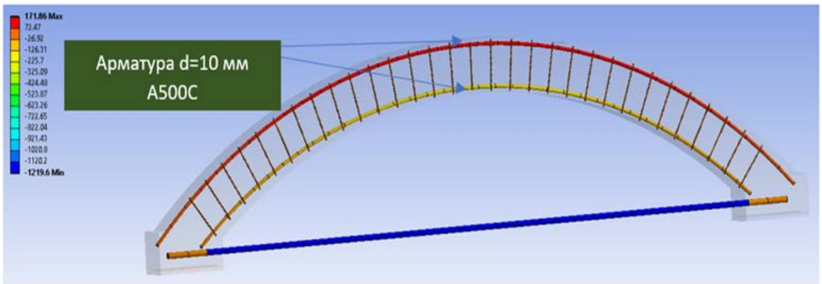

Fig. 10. Force in reinforcement (kg) in the arch at a load of P=10 kN.
Рис. 10. Зусилля в арматурі (кг) в арці при навантаженні P=10 кН.

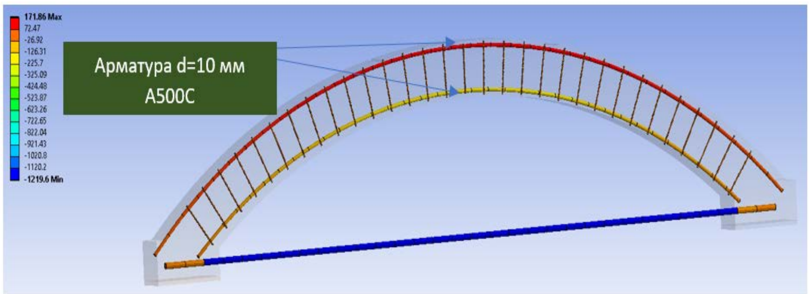

Fig. 11. Force in reinforcement (kg) in the arch at a load of P=50 kN.
Рис. 11. Зусилля в арматурі (кг) в арці при навантаженні P=50 кН.

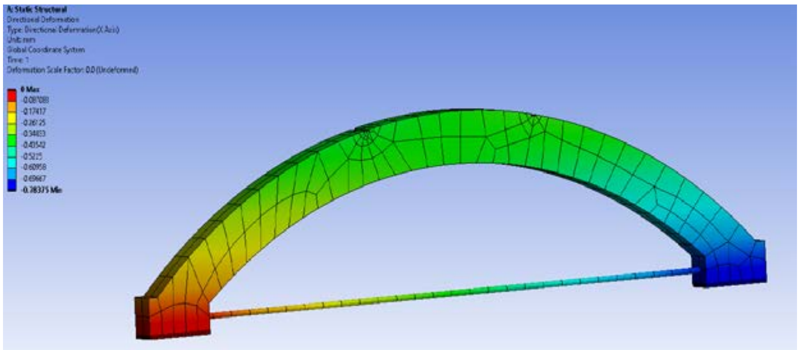

Fig. 12. Deflections (mm) in the arch under load P=10 kN.
Рис. 12. Прогини (мм) в арці при навантаженні P=10 кН.

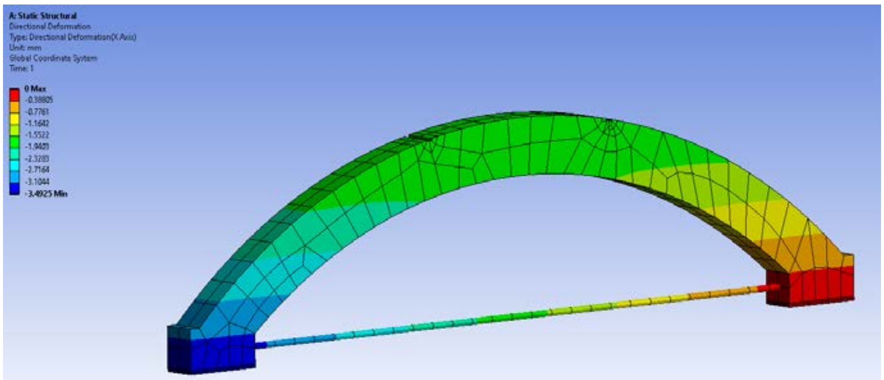

Fig. 13. Deflections (mm) in the arch under load P=50 kN
Рис. 13. Прогини (мм) в арці при навантаженні P=50 кН.

The results of comparing the numerical experiment data with the values ANSYS obtained from experimental studies [22, 23, 24, 25] are given in Table 1.

Table 1. Comparison of the results of numerical and experimental studies
Таблиця 1. Порівняння результатів числового та експериментальних досліджень

Load P, kN	$k=\frac{\sigma_{c,ANS}}{\sigma_{c,EXP}}$, MPa	$k=\frac{\varepsilon_{c,ANS}}{\varepsilon_{c,EXP}}$, $\times10^{-5}$	$k=\frac{N_{s,ANS}}{N_{3,EXP}}$, kN	$k=\frac{N_{s1,ANS}}{N_{s1,EXP}}$, kN	$k=\frac{f_{ANS}}{f_{EXP}}$, mm
10	$\frac{3,2}{4,0}=0,8$	$\frac{7,3}{6,83}=1,07$	$\frac{11,2}{5,0}=2,24$	$\frac{1,26}{1,65}=0,76$	$\frac{0,43}{0,51}=0,84$
50	$\frac{17,5}{23,46}=0,74$	$\frac{72,7}{86,1}=0,84$	$\frac{49,9}{23}=2,17$	$\frac{10}{11,54}=0,87$	$\frac{2,33}{3,84}=0,61$
k	0,81	0,87	1,93	0,86	0,73
σ	0,066	0,149	0,39	0,082	0,094
V_c, %	9,94	20,87	24,75	11,6	15,83

CONCLUSIONS AND RECOMMENDATIONS

The results of the calculation of the arch by the finite element method in the ANSYS have a satisfactory agreement with the data obtained from the results of experimental studies, with the exception of the values of tensile forces in the tightening, which, according to the results of the calculation in the ANSYS, significantly exceed the experimental values at the corresponding stages of the arch loading. The values of internal forces in the reinforcement and stresses in the compressed concrete of the arch belt obtained from the results of the calculation in the ANSYS correspond to the experimental data.

The values of internal forces in the reinforcement and stresses in the compressed concrete of the arch belt obtained from the results of the ANSYS calculation correspond to the experimental data, the standard deviation of the ratios is σ = 0.066…0.094, and the average value of the coefficient of variation is Vc = 12.5%.

The prospect of further research is the need for a more detailed study of the stress-strain state of reinforced concrete arches made of high-strength rapid-hardening concrete and the study of this structure on dynamic force effects. It is also necessary to investigate the nature of the stress-strain state of reinforced concrete arches with a uniformly distributed load on the belt.

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ЧИСЛОВІ ДОСЛІДЖЕННЯ РОБОТИ ЗАЛІЗОБЕТОННИХ АРОК НА ДІЮ СТАТИЧНИХ КОРОТКОЧАСНИХ НАВАНТАЖЕНЬ

Богдан КАРАВАН
Віктор КАРАВАН
Сергій ФІЛІПЧУК

Анотація. В статті описано методику експериментальних досліджень арки із високоміцного швидкотверднучого бетону, наведено в табличній формі результати досліджень та описано механічні характеристики матеріалів, які були використані при виготовленні дослідних зразків арок. Коротко описано процес виготовлення дослідних зразків з високоміцного швидкотверднучого бетону. Також наведено рисунки установки, на якій проводились дослідження напружено-деформованого стану залізобетонних двошарнірних арок на дію статичного одноразового короткочасного навантаження. Продемонстровано рисунки здеформованих та/або зруйнованих дослідних зразків.

Наразі виникає потреба в максимально швидких темпах зведення споруд різного призначення, що можливо досягнути шляхом введення в технологічний процес високоміцних швидкотверднучих бетонів, які дають змогу істотно збільшити темпи будівництва і відповідно зменшити терміни зведення будівель і споруд. Закономірності деформування при короткочасному статичному навантаженні високоміцних бетонів до цього часу вивчені недостатньо, що ускладнює розрахунки залізобетонних конструкцій з таких бетонів. Вирішенню цих задач присвячена ця стаття.

Існує необхідність вивчення напружено-деформованого стану залізобетонних арок з високоміцного бетону на дію статичних одноразових і повторних навантажень різного рівня та поглибленого визначення фізико-механічних і деформативних характеристик високоміцних бетонів. Це дозволить більш точно оцінювати напружено-деформований стан елементів залізобетонних конструкцій з таких бетонів, підвищити надійність проєктування і одержати істотний економічний ефект при зведенні будівель і споруд, що є актуальною задачею сьогодення.

Ключові слова: дослідження; експеримент; арка; бетон; випробовування; розрахунок.

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