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BEARING CAPACITY OF HINGELESS CIRCULAR ARCHES MADE OF CONCRETE AND FIBER CONCRETE UNDER HYDROSTATIC PRESSURE

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ABSTRACT

The authors presented a numerical and experimental study of the bearing capacity of circular concrete and fiber concrete arches The authors made a stand to determine the bearing capacity of arches models under hydrostatic pressure. The hingeless arches were made of C16/20 concrete; one arch was made of unreinforced concrete, and the second arch had 1% steel anchor fiber added to the mix. ANSYS software was used for computer modeling and numerical analysis by the finite element method. When testing the concrete arch, the breaking load was 710 kN, and when testing the fiber concrete arch, it was 810 kN, that is, the bearing capacity of the fiber concrete arch determined experimentally was 1.13 times higher. The results of experimental and numerical investigations agree well with each other and with the results of theoretical calculations. Comparison of normal stresses in the experiment determined at strain gauge points with their theoretical values gives a maximum discrepancy of 9.6 % for the concrete arch and 9.2 % for the fiber concrete one. It is recommended to increase the load-bearing capacity of the structure by means of a more uniform dispersed reinforcement of the arch.

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Introduction.

Arch structures are very widely used because, with the same carrying capacity, their material intensity is much lower than that of beams and frames. Arches are easy to make and install. They are made of different materials, but most often of reinforced concrete. The outline of the arch can be chosen so that the bending moments in the sections are small, which minimizes the main disadvantage of concrete — poor tensile performance.

The most economical and simple in design are the hingeless arches. Their disadvantage, as it is known, is the occurrence of additional bending moments in the sections in the case of uneven settlement or horizontal displacement of supports, temperature changes, as well as from creep and shrinkage of concrete.

The calculation of reinforced concrete arches is usually carried out in the elastic formulation. The classical theory of calculation of arches develops in two directions. The first direction is to determine the forces from external influences — the fixed and moving loads, temperature, displacements of supports, and installation forces. The second direction determines the selection of the rational outline of the axis, the value of the boom lift, and the law of change of cross-sections [1 - 4].

Recent Research Analysis.

Increasing the bearing capacity and crack resistance of arches seems possible through the use of new materials, in particular, fiber concrete, and building more accurate models of the work of the material and structure as a whole, which is associated with the capabilities of modern software and experimental modeling [5 - 8]. In foreign countries, many works are devoted to the study of arches, in which the results of numerical and experimental modeling are presented, but mainly the problem of stability is considered [9 - 12].

Let's dwell in more detail on the works related to the use of new materials. To increase the strength, stiffness, and plasticity of reinforced concrete arches, polymers reinforced with carbon fiber were used in [13]. Reinforcement was performed by gluing and wrapping. In [14] three reinforced concrete arches are experimentally investigated. One is used as a control, and the other two are reinforced with externally bonded strips of polymer fibers according to different schemes. Great work was done by the authors of the article [15]. Here a large series of concrete and fiber concrete arches were investigated. The behavior of the arches was evaluated using various mechanical properties, including the nature of failure, load-deflection ratio, deformation analysis, and analytical study. A finite element model was developed to account for physical and geometric nonlinearity. An experimental study of the behavior of reinforced concrete arches reinforced with glass fiber-reinforced polymer layers was conducted in [16]. A total of 36 specimens were tested, including 3 control and 33 reinforced concrete arches under concentrated load. The variables of this study were the reinforcement factor of steel reinforcement, the number of fiberglass layers, and the arrangement of the fiberglass layers.

The purpose of this work is to perform a numerical and experimental study of the bearing capacity of circular concrete and fiber concrete arches to obtain information on the feasibility of dispersed reinforcement.

Materials and Research Methodology.

The hingeless arches were made of concrete C16/20; one arch was made of unreinforced concrete, and the other with 1% steel anchor fiber was added to the mix. At the same time, specimen cubes with a rib size of 10 cm were made from these mixes and tested in compression according to [17]. To implement the scheme of loading the arches with hydrostatic pressure, a stand [18] was designed to determine the bearing capacity of the arch models. The load was applied in small steps to study the deformation process in detail. At each stage, we recorded the readings of measuring instruments, which used clock-type indicators and strain gauges. The ANSYS program [19] was used for computer modeling and numerical analysis by the finite element method.

Research results. The arch shown in Fig. 1 is outlined in an arc of a circle. The arrow of the lift is f = 100 cm, span is ℓ = 200 cm. The cross-section is rectangular.

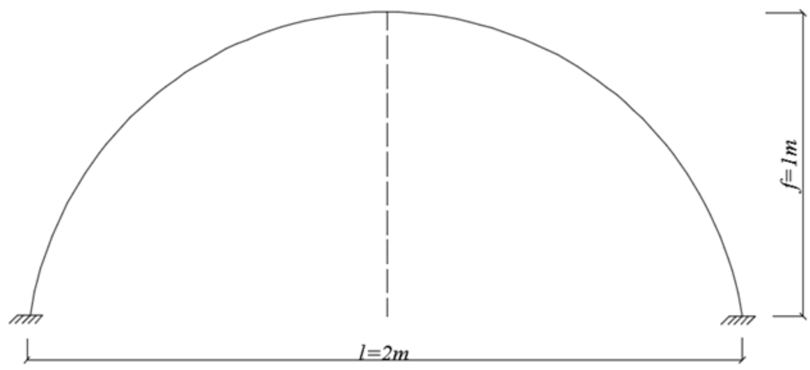

Fig. 1. Diagram of the arch

The arch under test 3 is mounted on loading beam 1, which is supported by four supporting struts 7. Strain gauges are glued on the side surfaces of the arch and indicators are fixed, with the help of which the deformations of the most loaded fibers of the arch material are monitored in the process of loading (Fig. 2).

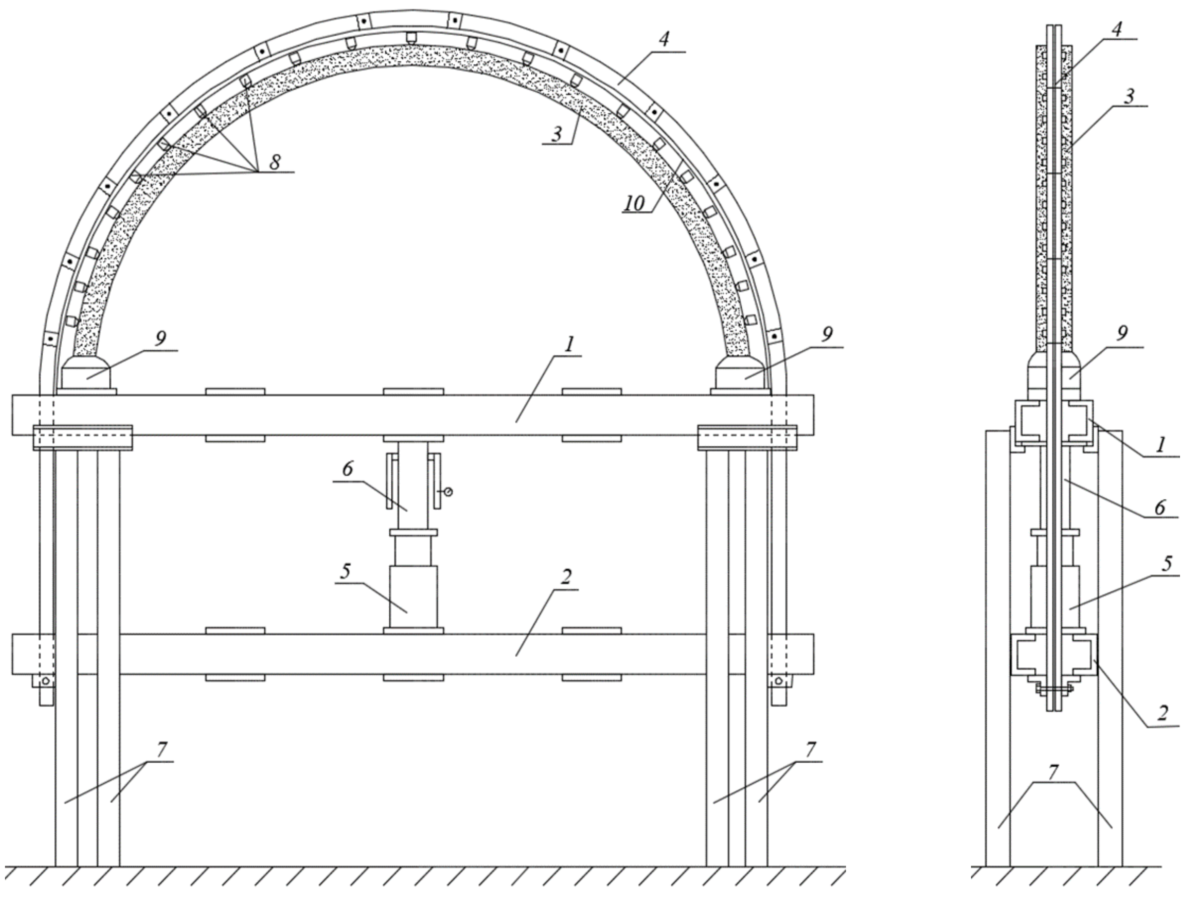

Fig. 2. Test bench: 1 – upper load beam; 2 – lower load beam suspended on chains; 3 – concrete arch; 4 – load chain; 5 – jack; 6 – reference dynamometer; 7 – support legs; 8 – rods transferring the load from the chain to the arch; 9 – supporting heel; 10 – auxiliary metal strip

On the upper external surface of the arch, there is a thin metal strip 10 to which transferring rods 8 are fastened with self-tapping screws every 12 cm. On strip 10 is a flexible lamellar rod 4, which encircles the arch on the upper belt. The strip 10, due to its low rigidity, takes the outline of the top chord of the arch and allows the lamellar rod to slide freely over the surface. The flexible lamellar rod is assembled from metal plates with a section of 50×5 mm and a length of 270 mm. Every 24 cm four pairs of plates on one side and four on the other are connected to each other alternately by high-strength bolts Ø16 mm. The total length of the flexible rod is 5 meters. The bolt connections (hinges) allow the flexible lamellar rod to take the outline of the top chord of the arch. The second (lower) loading beam 2 is attached to the lamellar rod 4.

In the process of loading, the lower beam 2 is shifted with the help of the jack 5 relatives to the upper beam 1, on which the arch 3 is supported. Displacement of the lower beam 2 leads to the fact that the flexible plate rod around the arch is stretched and a uniformly distributed load (hydrostatic pressure) is transferred to the arch over its entire surface. The force applied to the beams, and hence to the plate rod, is controlled with a sample dynamometer 6.

In the process of loading, the load applied to the lamellar rod, and hence to the arch, is recorded, as well as the corresponding deformations occurring in the concrete. The load is applied in steps. Each step ends with an endurance period of 5 to 8 minutes with the fixation of all necessary parameters. Deformations have been measured with strain gauges and clock-type indicators with a division price of 0.001 mm, and base 250 mm. Load cells base — 50 mm. The first and fifth load cells (Fig. 3) are located at the supports. The third one is in the middle of the span at the "lock" level, and the second and fourth are symmetrically at half of the lift arm.

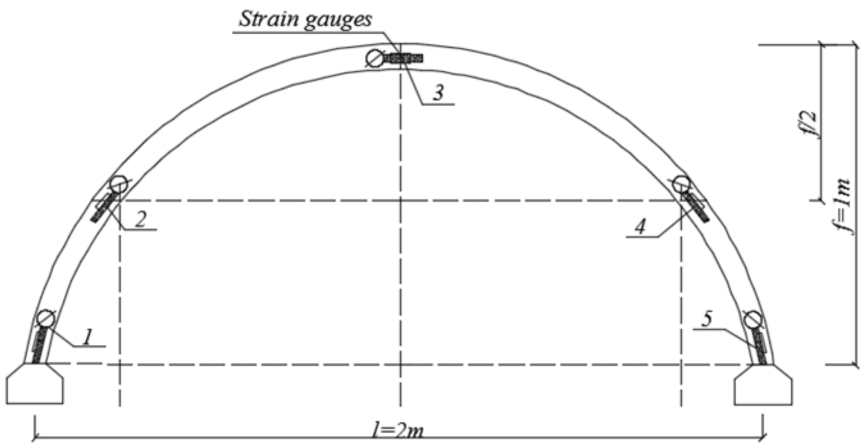

Fig. 3. Layout of load cells

Fig. 4 shows the deformation pattern of the concrete obtained during the loading process at the initial stage of the experiment. The graphs shown in this figure show that all the measuring instruments work synchronously and show almost linear dependence throughout the entire loading process. And this means that under this loading scheme there are almost equal stresses in all cross-sections of the arch. The loading process ends when the arch loses its ability to resist the load or collapses. The load value corresponding to this moment is taken as the bearing capacity of the arch.

Material characteristics of the tested arches: concrete: initial modulus of elasticity — $E = 2{,}5 \cdot 10^4$ MPa; Poisson's ratio — $\mu = 0{,}2$; fiber concrete: initial modulus of elasticity — $E = 3{,}1 \cdot 10^4$ MPa; Poisson's ratio — $\mu = 0{,}21$.

During the tests, both arches were brought to failure. The destructive load for the concrete arch was 710 kN and for the fiber concrete arch 800 kN. The processing of measuring instrument readings made it possible to determine the normal stresses corresponding to these loads (Table 1). The same table shows the theoretical values of stresses calculated according to the known method [20] for loads on the arches at the moments of their failure.

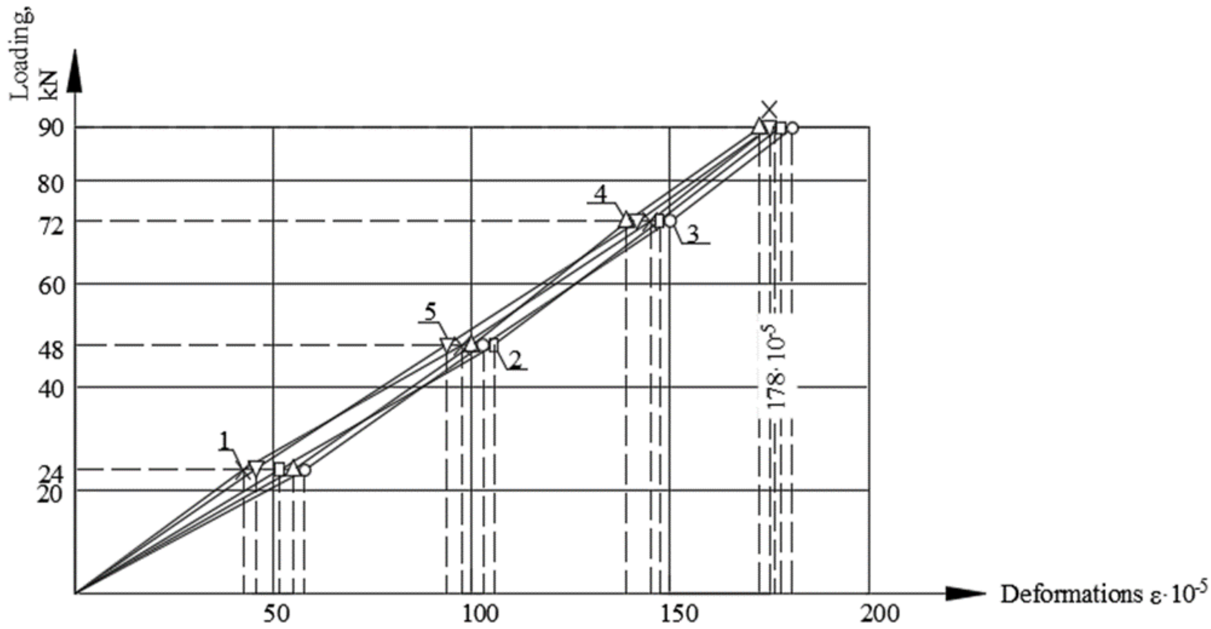

Fig. 4. Relative deformations according to indicator readings

Calculations in the ANSYS software package have also been carried out with the stresses corresponding to the destructive loads in the experimental studies. The normal stresses determined as a result of these calculations are given in Table 1, and in Fig. 5 shows the diagram of bending moments in a concrete arch, moreover, the maximum moment in a pinch equals 1.352 kNm, which agrees well with the theoretical and experimental values of this moment. It should be noted that the results of finite-element analysis depend significantly on the way the finite-element mesh is constructed. Results given here have been obtained by dividing the arc axis into 80 finite elements of equal length; if the arch span is divided into 80 identical parts, the lengths of finite elements will be different and the maximal moment in concrete arch wedging will be equal to 3,986 kNm. This fact is confirmed by our additional finite-element calculations in two other programs — PC LIRA-SAP and SOFiSTiK.

Table 1. Comparison of results for a concrete arch

№№ of points	σ_{theor}, MPa	σ_{num}, MPa	σ_{test}, MPa	Discrepancy σ_{theor} and σ_{test}, %
1	31,339	31, 854	33,441	6,3
2	-3,565	-3,624	-3,944	9,6
3	13,113	13,331	14,338	8,5
4	-3,565	-3,624	-3,266	8,4
5	31,339	-31, 854	33,844	7,4

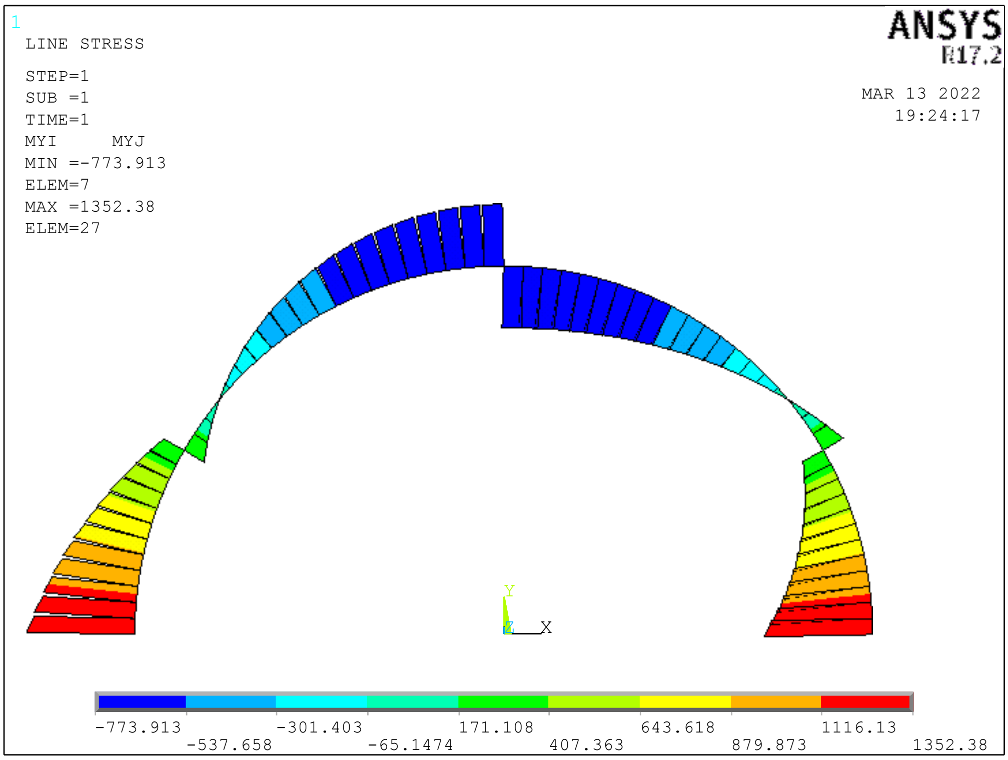

Fig. 5. Bending moment diagram in the concrete arch

Similar results for the fiber concrete arch are shown in Table 2.

Table 2. Comparison of results for a fiber concrete arch

№№ of points	σ_{theor}, MPa	σ_{num}, MPa	σ_{test}, MPa	Discrepancy σ_{theor} and σ_{test}, %
1	35,340	35, 920	34,124	3,4
2	-4,020	-4,087	-3,716	7,6
3	14,787	15,033	13,423	9,2
4	-4,020	-4,087	-3,777	6,1
5	35,340	35, 920	33,635	4,8

Conclusions.

When testing the concrete arch, a breaking load of 710 kN was achieved, and when testing the fiber concrete arch 810 kN, that is, the bearing capacity of the fiber concrete arch determined experimentally was 1.13 times higher. The results of experimental and numerical investigations agree well with each other and with the results of theoretical calculations. Comparison of normal stresses in the experiment determined in the points of strain gauge location with their theoretical values gives a maximum discrepancy of 9.6 % (point 2) for concrete arch and 9.2 % (point 3) for fiber concrete. It appears that the load-carrying capacity of the structure can be improved by more uniform dispersed reinforcement of the arch.

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