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Experimental studies of a reinforced concrete arch made of high-strength concrete on the action of low-cycle loads

Badania doświadczalne łuku żelbetowego wykonanego z betonu o wysokiej wytrzymałości na działanie niskocyklowych obciążeń

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Abstract. The methods and results of experimental studies of a reinforced concrete arch with tension, made of high-strength concrete, are given. The stress-strain state of the arch under the action of static short-cycle repeated loads of different levels before destruction is described, and its bearing capacity is determined. Graphs of the dependence of the load and deformation of concrete and reinforcement, the dependence of the deflections and displacement of the arch supports on the loads are given and described. The process of crack formation and development of cracks in a reinforced concrete arch under the action of repeated loads of different levels is described.
Keywords: concrete arched structures; high-strength and quick-hardening concrete.

Streszczenie. W artykule podano metodologię i wyniki badań eksperymentalnych łuku żelbetowego ze ściągiem, wykonanego z betonu o wysokiej wytrzymałości. Opisano stan naprężenie-odkształcenie łuku pod działaniem statycznych, krótkotrwałych, powtarzalnych obciążeń o różnych poziomach przed zniszczeniem oraz określono jego nośność. Podano i opisano wykresy zależności obciążenia i odkształcenia betonu i zbrojenia, zależności ugięcia i przemieszczenia podpór łukowych od obciążeń. Opisano proces powstawania i rozwoju pęknięć w łuku żelbetowym pod działaniem powtarzających się obciążeń o różnych poziomach.
Słowa kluczowe: betonowe konstrukcje łukowe; betony o wysokiej wytrzymałości i szybkowiążące.

Reinforced concrete arched structures are widely used in construction, starting from lintels of window openings, to covering structures of industrial and civil buildings (including as part of shell diaphragms), sports facilities, load-bearing span structures of bridges and crossings, aqueducts. Since 2014, and especially after the full-scale invasion of February 24, 2022, there has been an urgent need in Ukraine to restore existing and build new defensive fortifications and defense structures to protect the civilian population. One of the effective structural schemes of a protective building is a combination of structural elements erected from monolithic reinforced concrete and prefabricated elements in the form of two-hinged arches with a span of 2 m or more, made of high-strength concrete [1 – 5]. In the conditions of martial law, there is a need for the fastest possible pace of construction of defense (fortification) structures. This can be achieved by introducing high-strength quick-hardening concrete into the process, which makes it possible to significantly increase the pace of construction and, accordingly, reduce the construction time of buildings and structures.

The strength of concrete can reach 80 ÷ 150 MPa, and design standards in Ukraine for structures made of such concrete are under development [2, 4 ÷ 8]. Taking into account the small number of experimental studies of reinforced concrete arch structures and the lack of such studies of arches made of high-strength concrete, it is relevant to study experimentally the stress-strain state of arches made of high-strength concrete under the action of force influences of various nature and intensity. The purpose of the study is to develop a methodology for testing a reinforced concrete arch under the action of low-cycle repeated loading, followed by a study of the change in the stress-strain state of the arch cross-sections. Also, the goal was to investigate the nature of the destruction of the arch made of high-strength concrete and to obtain deformation diagrams.

Volume and methodology of experimental research

To carry out experimental studies, the main test sample was made in the form of a flat two-hinged reinforced concrete arch with a draw from high-strength concrete class C75 and auxiliary samples – cubes and prisms for determining the physical and mechanical characteristics of concrete [9]. The main mechanical and deformation properties of high-strength concrete, which were obtained as a result of tests of concrete cubes and prisms, are described in [10]. The arch had a calculated span of L = 200 cm, a full height of H = 52 cm, a lifting boom f = 40 cm, and a cross section of the curved belt of 10 (b)×14 (h) cm (Figure 1).

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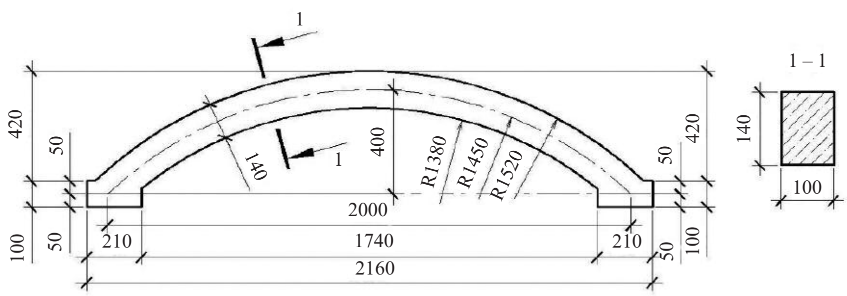

Fig. 1. Formwork drawing of the prototype of the arch (dimensions in mm)
Rys. 1. Szalunek przykładowego łuku (wymiary w mm)

Mechanical characteristics of concrete (cubic and prismatic strength) under a one-time short-term load were determined according to standard methods [11].

M500 Portland cement served as the binding material. When calculating the composition of concrete, the recommendations given in [12] were used. The reinforcement of the arches is symmetrical, it was carried out using a flat knitted frame, the rods of the working longitudinal reinforcement are Ø10 A500C, the transverse reinforcement of the frame is made of wire with a diameter of 4 mm Vr-1 with a step of 70 mm. A reinforcing rod with a diameter of 16 mm A500C was used as a tension. The arches were made in wood-plastic formwork, the concrete mixture was compacted with a deep vibrator.

The arch was tested in an installation mounted on the basis of a UYM-200 hydraulic press. The loading of the arch was carried out with the help of a hydraulic pumping station in stages, the value of which was 5 kN. The magnitude of the load on the steps was controlled by a D-1 dynamometer previously tared in a PG-250 hydraulic press. Using a rigid traverse, the load was applied to the arch belt in the form of two concentrated forces. At each stage of the load, a waiting period of 5-15 minutes was arranged to take readings from the devices, stabilize the deformations in the concrete, and fix the parameters of crack formation and the width of the opening of cracks in the arch belt. At load levels, the tensile and compressive deformations of the armatures and tightenings were measured using Hugenberger strain gauges based on 20 mm with a division value of 0.001 mm. Tensile and compressive deformations of concrete were recorded by mechanical indicators of the clock type 1(2) MIG with a division value of 0.001(2) mm on a base of 100 mm on average, which were fixed on the arch with the help of metal holders glued to the concrete surface with epoxy glue. The deflection of the arch was measured in the middle of the span using a 6PAO deflection gauge with a division value of 0.01 mm. Also, with the help of a 6PAO deflection gauge and a clock-type indicator ICH-10m with a division value of 0.01 mm, the movement of the arch on its two supports was measured. The general appearance of the experimental arch in the installation is shown in Figure 2.

The experimental reinforced concrete arch with tension was tested for the effect of static short-term low-cycle repeated loading until failure. The work [10] shows the results of testing one reinforced concrete arch with tightening under the action of a static one-time load, made of concrete of the same batch. Based on the results of the arch test, determine the destructive force Fu = 90 kN, which was taken as the critical destructive load in this study.

In the first cycle, the load was applied in steps (5 kN each) to the value F = 45 kN = 0.5Fu. After that, in steps of 10 kN, the arch was unloaded to the value F=18 kN = 0.2Fu. In the next 2÷10 cycles, the upper load level was F = 45 kN = 0.5Fu with unloading to the value F = 18 kN = 0.2F. At each level of load, holding times were observed to stabilize deformations in the concrete and remove readings. On the eleventh cycle, the load from F = 45 kN = 0.5Fu was increased to the value F = 67.5 kN = 0.75 Fu in steps of 5 kN. After that, the arch was unloaded to the value F = 18 kN = 0.2Fu. In subsequent cycles, the load on the arch was applied from the lower level of F = 18 kN = 0.2 Fu to the upper level of F = 67.5 kN = 0.75 Fu in steps of 20 kN. After the 19th cycle, the arch was destroyed by the load, which was applied in steps of 5 kN to the value of Fu = 90 kN.

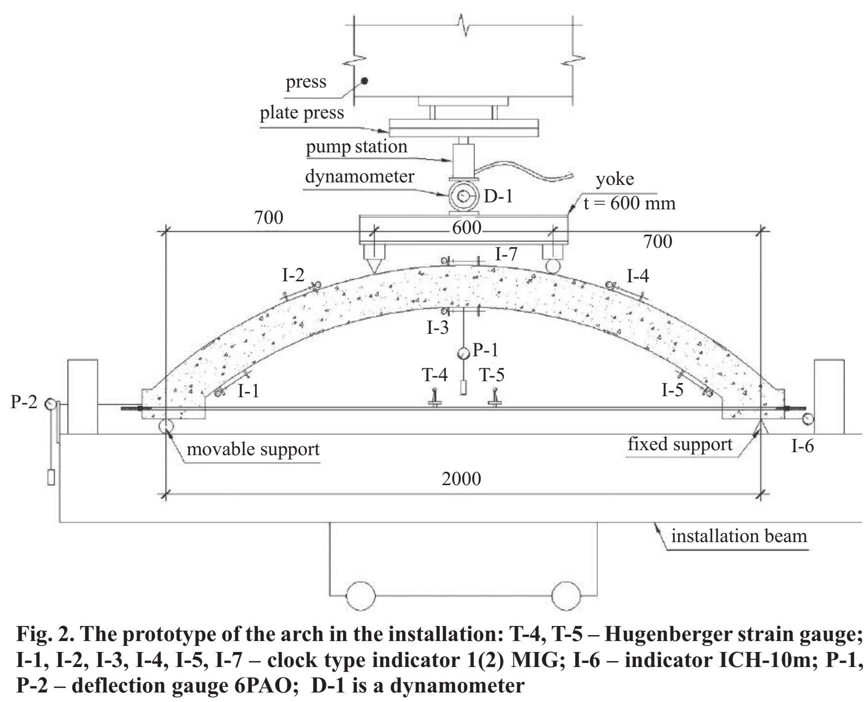

Fig. 2. The prototype of the arch in the installation: T-4, T-5 – Hugenberger strain gauge; I-1, I-2, I-3, I-4, I-5, I-7 – clock type indicator 1(2) MIG; I-6 – indicator ICH-10m; P-1, P-2 – deflection gauge 6PAO; D-1 is a dynamometer
Rys. 2. Przykładowy łuk na stanowisku badawczym: T-4, T-5 – tensometry Hugenbergera; I-1, I-2, I-3, I-4, I-5, I-7 – mierniki zegarowe 1(2) MIG; I-6 – miernik ICH-10m; P-1, P-2 – mierniki ugięcia 6PAO; D-1 dynamometr

Concrete cubes tested at the age of 28 days in a PG-250 hydraulic press had an average strength of $f_{cm,cube}$ = 88.5 MPa. The average strength of concrete prisms at the age of 28 days was $f_{cm,prism}$ = 75 MPa. The limiting value of the relative deformation of compression concrete was ε_{cu} = 180 ÷ 200×10^{-5}. The mechanical characteristics of the rods of working longitudinal reinforcement with a diameter of 10 mm A500S were determined by the results of tests of three samples 50 cm long in the UYM-50 breaking machine. According to the results of the tests, it was established that the yield strength of the reinforcement bars is σ_y = 522.3 MPa, and the strength limit is σ_u = 634.4 MPa.

Arch test results

When testing a reinforced concrete arch at load levels, the deformations of reinforcement and concrete were recorded in the compressed and stretched zones.

It can be stated that plastic deformations are significantly manifested in the compressed concrete during the first load cycle up to the level of 0.5Fu (Figure 3). Residual deformations of compressed concrete in the first cycle under a load of 0.2Fu were $\Delta\varepsilon_c$ = 52.9×10^{-5}. In subsequent cycles of repeated loading, without increasing its level, stabilization of deformations in compressed concrete is observed and it works almost elastically with a slight increase in the proportion of plastic deformations. For 10 load cycles, the increase in residual deformations in compressed concrete was $\Delta\varepsilon_c$ = 8.5×10^{-5}. When the arches were loaded to a load level of 0.75Fu, the relative deformations in compressed concrete increased with a significant increase in the proportion of plastic deformations, the residual deformations in the cycle at a load of 0.2Fu were $\Delta\varepsilon_c$ = 13.8×10^{-5} (Figure 3). During the next 10 cycles of repeated loading to the level of 0.75Fu, a gradual stabilization of plastic deformations in compressed concrete was observed, the increase in residual deformations for 10 loading cycles was $\Delta\varepsilon_c$ = 7.7×10^{-5}. The relative deformations of compression concrete at the last stage of loading were ε_c = 180×10^{-5}, which corresponds to its limit values (Figure 3). The relative compression deformations of concrete in the sections of the arch belt with indicators I-2 and I-4 did not reach their limit values, their maximum value was ε_c = 77×10^{-5}.

Significant deformations of concrete were recorded in the stretched cross-sectional area in the center of the arch (indicator I-3), which significantly exceeded the limit value ε_{ctu} = 10×10^{-5} already at the first load cycle. By analogy with compressed concrete, during the cycles of repeated loading and additional loading of the arch, an increase in deformations was observed in the stretched concrete, followed by their stabilization during subsequent loading cycles at an unchanged level (Figure 4). Under the destructive load, the relative deformations of tensile concrete were ε_{st} = 106.7×10^{-5}. Such large values of deformations are explained by the fact that cracks formed and opened along the length of the measurement base of the indicators.

The relative deformations in the compressed and stretched working armature of the arch belt under the destructive load were smaller than the values of the deformations at the yield point of the steel. The tensile deformations of the tightening armature increased linearly depending on the loads. Thus, on the tenth cycle at a load level of 0.5Fu, the relative tensile strains of the draw were ε_s = 57.5×10^{-5}, on the twentieth cycle at a load level of 0.75Fu, the relative strains of the draw were ε_s = 82.5×10^{-5}. When the value of the critical force Fu = 90 kN was reached in the arches, the relative deformations of the tensile stress were εs = 115×10^{-5}, which is less than the deformations at the yield point of steel. In general, as the load increased, the deformations in the reinforcement increased, but it can be concluded that the steel worked elastically before the failure.

The dependence of the change in the deflection in the middle of the span of the arch from the loads to the failure has a clearly expressed linear character (Figure 5). As the level of load on the arch increased, the deflection increased, with its subsequent stabilization during cycles of repeated loading. The deflection of the arch at the last level of loading before failure at Fu = 90 kN was f = 7.5 mm, which is less than the maximum allowable value according to the norms of fu = l/150 = 13.3 mm.

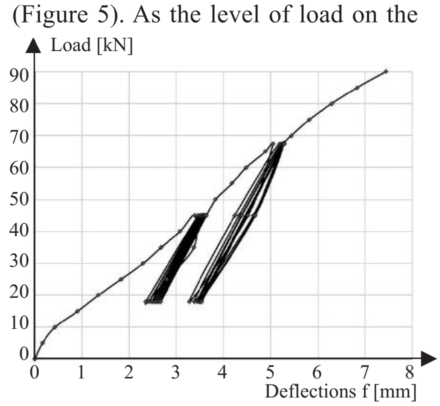

Fig. 5. Dependence of arch deflection on load
Rys. 5. Zależność ugięcia łuku od obciążenia

The total horizontal movement of the arch supports (as a result of the spacer) during the destructive load at the last stage was Δ = 8.8 mm. The nature of the „load – support movement" dependence in the arch is identical to deflections, namely: an increase in the load level cau-

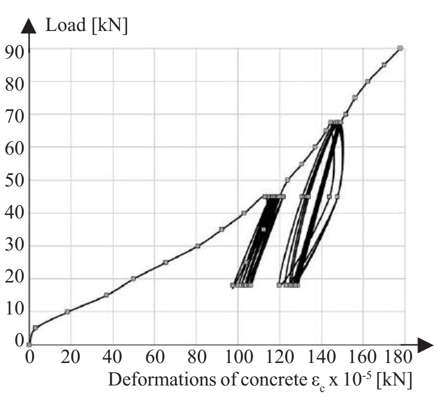

Fig. 3. Relative deformations of concrete in the compressed zone of the arch belt according to indicator I-7
Rys. 3. Odkształcenia względne betonu w strefie ściskanej łuku wg miernika I-7

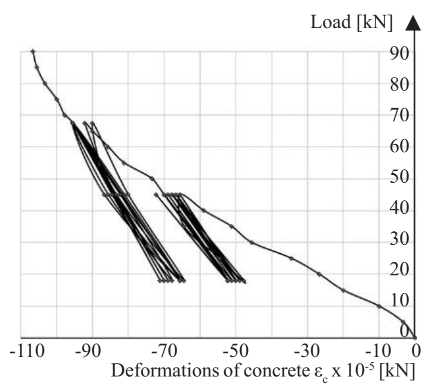

Fig. 4. Relative deformations of concrete in the stretched zone of the arch belt according to indicator I-3
Rys. 4. Odkształcenia względne betonu w strefie rozciąganej łuku wg miernika I-3

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ses an increase in the values of linear movements on the supports, after repeated loading, they stabilize with a slight increase in cycles (Figure 6). The magnitude of the deflection during the load cycles of the arch is a commensurate value of the total movements of its supports.

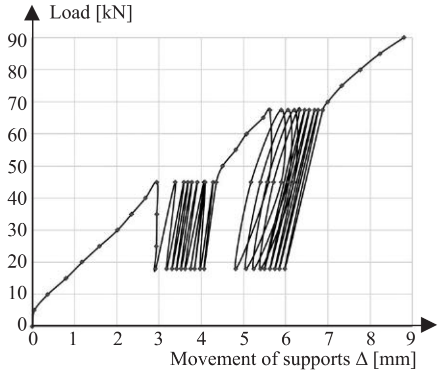
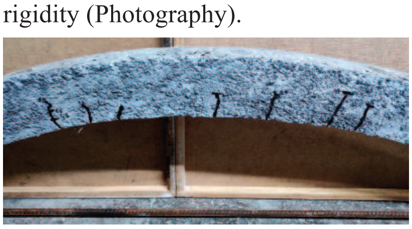


Fig. 6. Dependence of total displacement of arch supports on loads

Rys. 6. Zależność całkowitego przemieszczenia podpór łuku od obciążeń

The first vertical crack was formed in the section under concentrated force in the lower zone of the arch belt at the 14th cycle (degree 48) under the load F = 67.5 kN. The crack opening width was w_k = 0.04 mm. In subsequent cycles of repeated loading, the formation of new and development of existing cracks was not observed. On the 20th cycle, under a load of F = 70 kN, two new cracks formed in the lower zone of the arch belt under concentrated forces. The crack opening width was w_k = 0.1 mm. With an increase in the load for 20 cycles, the development of existing and the formation of two new vertical cracks in the sections of the arch belt was observed. At a load of F = 90 kN, the opening width of the main (critical) crack was w_k = 0.1 mm, with further loading of the test arch, the crack opening width was w_k = 0.3 mm. Normal through cracks broke the belt of the arch into separate blocks, it lost its rigidity (Photography).



The arch with contours of cracks after the test

Łuk z miejscami pęknięć po badaniu

Conclusion

According to the results of experimental studies, the destructive load for the arch, under the action of static low-cycle repeated loads, was Fu = 90 kN, which corresponds to the destructive load for the arch of the same series, which was subjected to the action of a static one-time short-term load [10].

In a double-hinged reinforced concrete arch with tensioning made of high-strength concrete, due to the formation and development of cracks, as well as the growth of plastic deformations in the concrete, a change in the stress-strain state occurs with a redistribution of internal forces in the sections of the upper belt along its length. The arch belt works as a compressed-bent element.

The relative compression deformations of the concrete during the arch failure reached the limit values. During cycles of repeated loading, without increasing its level, stabilization of deformations in compressed concrete is observed and it works almost elastically with a slight increase in the proportion of plastic deformations.

The relative deformations in the compressed and stretched working armature of the arch belt under the destructive load were smaller than the values of the deformations at the yield point of the steel. The tensile deformations of the tightening armature increased linearly depending on the loads.

The dependence of the change in the deflection in the middle of the arch span from the loads to the failure is linear. The first cracks in the arch belt made of high-strength concrete are formed at the load level F = 0.75Fu, at a constant level (less than 0.75Fu) of repeated loading, new cracks do not form, and the development of existing cracks stabilizes.

The obtained results can be used for further study of the stress-deformed state of reinforced concrete arches made of high-strength, quick-setting concrete, because scientific research on this topic was practically not conducted. In the future, this design is planned to be used as the main element of the arched covering of small-fire points. High-strength concrete, which is the main material of the experimental arch, will reduce the construction time of defensive structures and increase the reliability of the structure. The obtained results of the study will allow to start conducting tests of arches under the action of dynamic loads with further implementation of the work results in full-scale models.

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