Experimental research of masonry arches under the influence of the movement of supports

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Abstract. The authors of the article investigate new design solutions for the restoration of damaged masonry vaults and arches. The article presents the results of experimental studies of the deformability of reinforced and unreinforced masonry arches on lime-sand solutions during normal operation with a fracture factor (horizontal and vertical movement of the support). During the study numerical and physical experiments were carried out. The article also presents the results of observations of the basement floor of the building of the Kazan Hotel on Bauman Street, Kazan, Russia. The study allowed authors to determine the deformation and crack formation of masonry arches. The experiment included a test of an unreinforced arch, until damage was obtained when a support movement occurred. At the second stage of the experiment, the damaged arch was strengthened by the developed method, and its further testing was carried out. The study allowed authors to determine the vertical displacement of the arch before and after amplification. According to the test results, one can make an assumption about the change in the deformability and destruction of the reinforced masonry arch. The reason for this may be a halt in the development of cracks that have appeared and a change in vertical displacements.

Keywords: buildings, construction, masonry, FRP, arch, vault.

1 Introduction
The construction of masonry buildings and structures in Russia began in the 10th century CE. Then, mainly masonry vaults were used as floors of buildings, most of which have existed to this day. In this regard, questions about strengthening such structures in order to maintain their bearing capacity for the further operation of buildings arise.

From a review of literature published from the 19th to the beginning of the 20th centuries in Russia, such as V.R. Berhardt, N.K. Krivoshein, N.K. Lakhtin, structural designs and features of masonry vault of buildings built before the beginning of the 20th century were observed.

According to the studied literature in Russia, the design of arches is very different from the arches built in Italy [1-4], Turkey [5], USA [6] and India [7], which introduces some details into the study. Some vaults were laid out without the use of bricks, clay pots were used instead [8]. Most of the arches built in Spain [9] and Italy [10] use plates, which is very different from the experience in Russia. Despite of the fact that masonry vaults are not used in Russia now, vaults are still being built in Africa [11-13], Iran [14] or still built in the last century in Cuba [15].

Figure 1. Vaulted floor structures in Russia.
In Russia, arches were studied by such scientists as P. T. Mikhailov, N. N. Polikarpov, K. S. Zavriev, Yu. V. Krotov, V. I. Rudnev, A.V. Belov, N.K. Snitko, V.A. Gastev.

Such foreign scientists as Leire Garmendia, Ignacio Marcos, Enrico Garbin, Maria Rosa Valluzzi, Silvia Briccoli Bati, Luisa Rovero, Philippe Block, Matt DeJong, John Ochsendorf, Mario Como, Maria Ricamato, Philippe Block did research on arches strength and deformability.

Theoretical and experimental studies in the field of stone arch bridge designs for static and dynamic loads were developed by such scientists as: J.F. Chen, H. Tao, Lucio Nobile, V. Bartolomeo, M. Bonagura, D.V. Oliveira, C. Lemos, P.B. Lourenco, S.W. Garrity, C. Melbourne, J. Wang, A.K. Tomor, Rosa Guimarães Atalaia Canhão.

In Russia, in the second half of the 19th - beginning of the 20th centuries, V.R. Bernhardt, N.K. Krivoshein, N.K. Lakhtin worked out theoretical questions in the field of masonry arch design.

To get more information about the work of masonry vaults built in Russia, the building of the Kazan Hotel on Bauman Street in Kazan (Russia) was investigated (Figure 3). In this building, the main reasons for the destruction and deformation of 48 masonry vaults were found, these are the horizontal and vertical movement of the supports.

**Figure 3.** 3D model of the basement of the Kazan Hotel.

In one part of the building, cracks in the lateral supporting arches were found (Figures 4, 5). Such defects are characteristic external sign of subsidence of the central pillars. This happened due to the
difference in the sediment of the continuous foundation and pedestal footing of the supporting structures.

![Figure 4. 3D model of a building block with defects.](image)

![Figure 5. 3D model of a building block with defects.](image)

It has been determined that ancient arch systems, like other space structures, are capable of partial changes or a complete change in the initial model due to their hidden reserves. This is confirmed by many examples of deformed structures that have lost some of the vertical supports, wall arches, ties, or other elements that are fundamental in the initial model [14, 16].

It has been determined that all types of destruction and deformation of the vaults are the failure of one or more of the conditions for the existence of spacer structures. In further studies, horizontal and vertical movements of the supports have been taken as the main factor of damage to the arches, because according to the studied literature [17-20], it have a stronger effect on the change in the stress-strain state of arch systems.
2 Materials and methods
In this article, the aim of the study is to obtain experimental data on the deformation and crack formation of damaged and reinforced masonry arches on lime-sand mortars with the maintenance of fracture factors (vertical and horizontal movement of the support).

The following tasks are set:
1. To study the deformability of arches on lime-sand solutions during normal operation with the introduction of fracture factors.
2. To determine the cracking of the arches at all stages of the work.
3. To analyze and compare the experimental data of the work of arches with horizontal and vertical movements of the supports of the arches.
4. To study the deformation of the arch reinforced by the method developed by the authors of this article with the introduction of fracture factors.

The test program is shown below (Table 1).

Table 1. Test Program.

| Stage | Experiment description | Damage factor | Support movement, mm | Model |
|-------|-------------------------|---------------|----------------------|-------|
|       | Experiment series 1     |               |                      |       |
| Stage 1 | Arch with maintaining the factor of destruction (vertical movement of the support). | Vertical movement of the support | 0 to destruction |       |
|       | Experiment series 2     |               |                      |       |
| Stage 1 | Arch with maintaining the factor of destruction (horizontal movement of the support) and modeling damage | Horizontal movement of the support | 0 to destruction |       |
|       | Experiment series 3     |               |                      |       |
| Stage 2 | Arch with maintaining the factor of destruction (horizontal movement of the support) | Horizontal movement of the support | 0 to 10 mm |       |
| Stage 3 | Damaged arch reinforced with composite materials | Horizontal movement of the support | 0 to 60 mm |       |
Before experimental studies of stone arches, there was a numerical study using ANSYS. The main goal of numerical research was to study the stress-strain state of masonry arches without damage and with actually detected damage. To study the work of arches, a heterogeneous (Figs. 6, 7) and homogeneous (Figs. 8, 9) structures of the arches were built. Various arch construction methods in Ansys strongly influence the results, which are confirmed by the studies described in [21]. The parameters of the materials for construction were taken according to a physical experiment.

![Figure 6. Vertical deformations of a heterogeneous masonry arch.](image1)

![Figure 7. Stresses in a heterogeneous masonry arch.](image2)

![Figure 8. Vertical deformations of a homogeneous masonry arch.](image3)
Numerical experiments helped to establish the reasons and confirm the theory published in [22] that in most cases spacer systems, vaults depend on the state of structures that hold the spreader, that is, on the connection frame, buttresses, adjacent floors, etc.

The analysis of the results obtained during the numerical studies made it possible to develop technical measures for strengthening masonry arches and vaults.

The method is based on the introduction of composite rods into the body of a stone arch in certain places [23]. Similar studies in this direction were published in [24].

The developed amplification method is shown in (Figure 10). Many authors [25–28] conducted numerous studies of stone arches and arches reinforced with FRP materials and show many positive qualities. Particular attention should be paid to the adhesion of the reinforcing element to the masonry, which was studied in [29].
Figure 10a. The scheme of strengthening masonry arch. 1 - the upper chase, 2 - the lower chase, 3 - the hole, 4 - masonry arch, 5 - prime coating, 6 - adhesive, 7 - reinforcing element, 8 - top layer.

In the laboratory, brick arches were made of ceramic bricks in accordance with Russian GOST 530-2012 using mortar with sand and mortar with strength M4, with the geometric characteristics shown in Figure 11.

Figure 11. The geometric dimensions of the tested arch. Names and places of movement indicators.

To simulate changes in the stiffness of the support (flexibility of the supports), vertical and horizontal movements of the supports were selected. Shifts were created using specially designed installations. The movement was carried out by its own weight of the arch, by means of gradual and controlled adjustment of the screws (Figure 12).

Figure 12. Installation for testing the masonry arch on the movement of the support.
For testing reinforced masonry arches, a Sika Wrap Hex 230C carbon fiber canvas was chosen. It has the following characteristics (properties of the initial fiber): elastic modulus - 230 GPa, tensile strength - 3450 MPa, elongation at break - 1.5 %, surface density - 230 g/m², fabric thickness - 0.12 mm.

The reinforcement of the brick arches by the developed method was carried out according to the following technology: the surface of the masonry in the areas of the strip stickers was cleaned of dust and cleaned with sandpaper; the cleaned surface was covered with a special primer Sikaepocem medul (water dispersion of epoxy resin).

Carbon fiber canvas cut into strips with a width of 15 mm was glued to the surface of the brickwork of the arch in one layer using glue based on Sika dur epoxy resin. The strip sticker was produced along the entire length of the arch continuously without tears and overlaps according to the developed method.

**Figure 13.** Reinforcement of the lower surface of the masonry arch with carbon fiber strips.

**Figure 14.** Reinforcement of the upper surface of the masonry arch with carbon fiber strips.

The arches tested in series 1 and 2 of the experiments are reference (not reinforced) samples. The test results of the reference samples made it possible to evaluate the effectiveness of the reinforcement method proposed in this work using composite materials of damaged masonry arches. Tests of the samples were carried out according to Russian GOST 8829-94.
At the beginning and at the end of each stage of the support movement, masonry deformation measurements were made using indicators with an accuracy of 0.01 mm. To measure the vertical displacements of the arch, indicators (No. 1, No. 2, No. 3) were installed in three places (Figure 11). The magnitude of the vertical and horizontal movements of the arch support was measured by an indicator (No. 4) mounted on a movable support (Figs. 11, 12).

3 Results
According to the results of tests of the 1st and 2nd series of arches, comparative diagrams of the dependencies between the size of the displacements of the arch supports and the vertical displacements at three points were constructed (Figs. 15, 16).

![Figure 15](image1.png)

**Figure 15.** The diagram of the vertical displacements of the arch during the vertical movement of the support. Names and places of indicators in Figure 11.

![Figure 16](image2.png)

**Figure 16.** The diagram of the vertical displacements of the arch with the horizontal movement of the support. Names and places of indicators in Figure 11.
Comparing the results of the diagram (Figs. 15, 16), it is possible to draw conclusions:

With the vertical movement of the support, the nature of the vertical displacements of the arch up to 14 mm has an indefinite dependence. When the displacements of the support range from 16 to 24 mm, the displacements have a clear linear relationship and constant growth. Further, with a settlement of more than 24 mm, the deformation of the arch changes significantly, as evidenced by a change in the growth of indicator No. 1.

With horizontal movement of the support, vertical movements have a linear dependence of only up to 10 mm of movement (until a crack is formed in the upper part of the arch). After the hinge (crack) is formed, the vertical displacements change significantly. The movements of the left part of the arch and the upper part of the arch are 1.7 times higher than the vertical movements of the right part of the arch.

Analysis of the test results of unreinforced masonry arches allows us to note the following:

It was found that when moving cracks that divide the arch into four independent blocks appear. Cracks correspond to hinges, turning the structure into an instantly changeable multi-joint model.

Comparison of the results of series 1 and 2 shows that the greatest influence on the strength of the arch is affected by horizontal movement. Therefore, in the 3 series of tests, the horizontal movement of the support is taken as a destructive factor.

Our studies have allowed us to determine all the stages of the arches during normal operation (without amplification); the mechanisms of destruction and study the deformability and crack formation of a masonry arch.

According to the results of tests of the third series (which was of two stages) of masonry arches, comparative diagrams of the dependencies between the horizontal movement of the arch support and the vertical displacements at three points were built (Figure 18).
Comparing the results of the diagram that was obtained when testing the third series of arches, we can draw the following conclusions:

The vertical displacement of the arch in the first stage (unreinforced) and the second stage (reinforced) has been changed. From the diagram we can see when moving up to 10 mm, the displacements of the left part of the arch and the upper part of the arch were 1.7 times higher than the right part. Experiencing a reinforced arch when the movement of the arch support is from 20 mm to 28 mm, the vertical displacements become equal, which indicates a change in the design model of the arch.

**Figure 18.** The diagram of the vertical displacements of the reinforced and unreinforced arch with the horizontal movement of the support. Names and places of indicators in Figure 11.

**Figure 19.** Destruction of the reinforced arch with a maximum horizontal movement of the arch support of 200 mm.
Figure 20. Cracks in the reinforced masonry arch. Arch support (left). The upper part of the arch (right).

4 Discussions

According to the test results, one can make an assumption about the change in the deformability and destruction of the stone arch reinforced with composite materials. This is indicated by a halt in the development of cracks and a change in vertical displacements. Closing the hinges leads to the inevitable transformation of the model into a new one, which is also confirmed by many foreign researchers [30–33].

As a result of the study, it was found that the proposed method of strengthening masonry arches and vaults can significantly increase the bearing capacity.

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