Numerical study on masonry vaults reinforced by composite

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Abstract. The article describes numerical study of masonry vaults, based on steel beams, reinforced with carbon fiber composites. Two amplification systems were investigated: a solid mortar with an embedded grid and a discrete one in the form of tapes (stripes). Numerical simulation based on nonlinear analysis revealed the amplification efficiency under different arrangements, cracking and destructive load, the stress-strain state of the vaults. Many models are considered: not strengthening; not strengthening with damage; reinforced without damage, reinforced with damage. The simulation results in ANSYS PC were compared with each other to assess changes in the bearing capacity and the nature of the destruction of the samples. The span of steel beams is 5 meters, the span of the arch is 1.1 meters, the rise of the arch is 120 mm, the thickness is 120 mm. The load on the vaults is applied evenly distributed. The material of the vaults is ceramic solid brick on a lime-cement mortar. The experimental results on unreinforced structures are compared with those obtained on the strengthened ones in terms of failure mode, maximum load, stiffness and ductility.

Key words: masonry vaults, strengthening and repairing, carbon fiber reinforcement, numerical simulation.

1 Introduction

In Russia, a lot of buildings, architectural monuments with ceilings from brick arches on metal beams, have been preserved. Such buildings are often in disrepair due to physical deterioration of materials or due to changes in power loads. Under reconstructing objects of cultural heritage, the replacement of historical structures is not allowed; therefore, special attention should be paid to their repairing without significantly changing the appearance of the structure. The traditional methods of reinforcing masonry structures – steel and reinforced concrete jackets, metal tire and pads, re-laying of masonry are laborious, costly, change the appearance of the structure. Therefore, the methods of reinforcing masonry with composite materials in Europe are widely used for the last two decades more attractively [1, 2]. These materials add greater tensile strength to structures, at the expense of a slight increase in weight, the possibility of application for any form and shape of reinforced structures. The builders are offered many systems, among which one can distinguish fiber-reinforced mortars, mortars reinforced with grid, composite materials in the form of separate bundles, lamellas (stripes) and textile installed on an organic basis. The widespread use of such materials is constrained by the lack of calculation methods that make it difficult to determine the effectiveness of various amplification systems. To form the calculation method it is necessary to obtain a clear understanding of the nature of the stress-strain state of the structure before and after strengthening. The desired picture can be obtained in the framework of numerical and natural experimental studies. Studies of the use of various composite systems for strengthening structures are relevant for engineers and builders.

Researchers have proven the effectiveness of reinforcing masonry walls, arch and vaults with composite materials. A wide variety of materials has been studied, for example, fiber textile coupled...
with a lime-based matrix and carbon fiber textile associated with a cement-based matrix, glass fiber-reinforced polymer meshes with a mortar. In the work of Longo and others [3] the mechanical properties of tensile strength and bending of a mesh of a fibrous mesh embedded in a mortar (inorganic matrix) are investigated. In this case, various fillers of the mortar affecting the heat efficiency of the amplification system are considered. A Dalalbashi analyzed in the study the test results of 150 samples of fiberglass and metal reinforcing fabrics immersed in lime-based mortar to determine their adhesion [4]. Such composites were used in various versions of the experimental strengthening of the walls of a historic building [5], which confirmed the effectiveness of their use. Other authors compared the effectiveness of using FRP- (polymer reinforced with fiber) and TRC- (solution reinforced with textile) composites when placed in strips [6]. This solution gains an appreciable economic effect of the decrease in the composite rate. The issues of adhesion of carbon fiber reinforced elements to the masonry are considered in the work of Mario Fagone [7]. The experimental results showed that the anchoring efficiency is highly dependent on the shape ratio of the samples. An extensive study of a carbon fiber mesh and a shotcrete pre-mixed mortar (CFRP-RR) based on lime, designed to restore old load-bearing masonry walls, was carried out by the Guerreiro team [8], taking into account amplification on one or two sides of the sample. In the next work, three types of TRM are experimentally investigated, which include steel, carbon and basalt textiles embedded in cement matrixes used as shear reinforcement for stone panels[9]. Comparison with unreinforced masonry made it possible to establish the degree of increase in the required strength in the shear zones.

Physical experiments were carried out not only with walls, but also on separate samples (for example, arches) and on full-scale models of reinforced vaults. This compares the results of unreinforced and reinforced with the help of two types of TPM-composites of arches at a scale of 1: 2, tested under vertical load [10]. In another work investigated full-scale masonry vaults, provided with buttresses and backfill, reinforced with basalt textile-reinforced mortar (BTRM) overlays either at the intrados or at the extrados under cyclic loads [11]. Both hardening solutions have proven effective in delaying cracking and increasing bearing capacity and stability. In another work by the same authors, the results of strengthening fragments of vaults using Steel Reinforced Grout (SRG), comprising ultra high tensile strength steel cords, bonded with lime-based mortar either to the extrados or to the intrados[12]. This method of amplification allowed increasing the stability and strength of the arch by 2-3 times.

An article by researchers from Politecnico of Milan analyzes the characteristics of ancient stone arches and vaults reinforced with composite systems [13]. Tests were conducted on the site on ancient stone arches and arch elements. In particular, three cylindrical arches and two arches were tested, either unreinforced or reinforced with steel reinforced mortar (SRG), textile reinforced mortar (TRM) and fiber-reinforced polymer (FRP). The failure mode, maximum load, stiffness and ductility are set for the results of reinforced and unreinforced structures. In the next work, the TRM amplification efficiency was estimated taking into account the mobility of the vaults supports [14]. Obtained experimental confirmation reduces the amplification efficiency of sliding or vertical movement of the supports. In many articles, experimental studies are supplemented by numerical ones, which allow a more detailed study of the reinforced element.

However, the reinforcement of brick vaults combined with metal beams is less studied. This design in the restoration practice is called "Prussian vault" and is often found in civil buildings of the late 19th–early 20th century in the city of Kazan. It should be noted that the arches of the late 19th century were most often performed on rails, and the beginning of the 20th century on steel rolling beams. Such constructions are used in the building of the Shamov hospital, psychiatric hospital, and a number of profitable and private residential buildings that are objects of cultural heritage of local and federal significance. The characteristic defects amounts authors include: the presence of holes in the vaults, soaking masonry cracks – that can affect the load-bearing capacity and deformability of overlap, reducing them several times. Inspection of many buildings with arches in the city of Kazan made it possible to supplement the list with such damages as corrosion of steel beams, leading to a decrease in their cross section and soaking of masonry with strength reducing.
An experimental study of unreinforced arches on steel beams was carried out in St. Petersburg, but concrete was the material of the vaults [15]. In the same place, in the "Warehouse" building, field tests of damaged stone vaults on I-beams were conducted and various methods of reinforcing with composites were studied using ABAQUS PC.

In the numerical research of Bespalov V. (St. Petersburg) [16] received the following character of stress-strain stage of vaults:

1) a network of micro cracks forms in the reinforced and unreinforced masonry;
2) one of the micro cracks begins to develop - for non-reinforced masonry, it is destructive; at the reinforced masonry, the composite mesh at a certain stage prevents the further development of the crack and, as a result, after stopping its growth, the next crack begins to grow;
3) the destruction of the reinforced masonry occurs when the ultimate tensile strength is reached due to an increase in shear stresses due to the difference in the deformations of the arch material and the reinforcing elements.

Thus, it was concluded that it is necessary to choose a reinforcement system in which the deformation indices are closest to the masonry. A similar nature of the destruction was obtained by other researchers for "classical" arches.

There are many ways to strengthen the vaults by summing up the unloading structures, the device of a concrete slab and shell, the device of plastering from polymer-lime compounds on an expanded mesh. However, these methods can change the arch configuration or increase the load on the beams. Reinforcement with reinforced mortar is ineffective with insufficient bearing capacity of steel beams.

Based on the foregoing and the results of a survey of real objects, for the present study we determined the geometric characteristics of the arches, their characteristic defects and selected two amplification systems using carbon polymeric materials. The main characteristics of the materials are shown in table 1. The advantages of these amplification systems include high bearing capacity, small dimensions and low specific gravity, as well as its versatility and the possibility of application for any shapes and shapes of reinforced structures.

Table 1. Main characteristics of the reinforcement system.

| Type of system      | Tensile strength, MPa | Elastic modulus, MPa |
|---------------------|------------------------|----------------------|
| Ruredil X Mes       | 48000                  | 240                  |
| CarbonWrapTape      | 98000                  | 245                  |

The first of them is actively used in Europe when strengthening reinforced concrete, stone and brick arches and vaults. Ruredil X Mesh is an international patented system for reinforcing building structures, consisting of a carbon fiber net and a mortar used as Portland cement adhesive with pozzolanic and other additives that are chemically, physically and mechanically compatible with masonry. The second, external reinforcement system Carbon WrapTape 530/600 – unidirectional carbon fiber tapes made from carbon fibers obtained by high-temperature exposure to organic fibers in an inert environment. The system also found wide application in the restoration, repair, reinforcement, seismic reinforcement of reinforced concrete, concrete, stone, steel, wooden structures.

Work on strengthening the structures under consideration by external reinforcement CarbonWrapTape involves the following main stages:

- restoration of the integrity and geometric shape of the reinforced structure (including, if necessary, anti-corrosion measures for beams);
- restoration of brickwork performance with wear over 40% by injection of polymer-cement compositions;
- preparation of the surface of the structure in the places of the device of the reinforcing elements in accordance with the design of the sticker scheme – surface treatment of the reinforced masonry structure with metal brushes to create roughness (up to 0.3 mm) to ensure reliable adhesion of the
binder to the surface of the structure, metal structures are not polished, surfaces are blown with air 3-5 times for dust removal;

- preparation of a binder (adhesive) - CarbonWrapResinLaminate+ (A two-component epoxy adhesive, component A of which is a thixotropic mixture of epoxy resins, active diluents, fillers, pigments and target additives, component B is a polyamine hardener containing filler and special additives), applied with a thickness of 3-5 mm, does not require separate primers;

- sticker reinforcing elements in two layers for beams;

- application of a protective coating (plaster).

The CBA device (external reinforcement systems) is allowed to be carried out in the temperature range of ambient air and structures from +5 °C to +45 °C and air humidity not more than 80%. The temperature of the structure must be at least 3 °C above the dew point temperature. The moisture content of the structure in the amplification zone should not exceed 4%. The width of the reinforcement bands varies from 50 to 600 mm, the maximum number of layers is 5. The maximum distance in the light between the tapes should be taken no more than a smaller value from: 0.2L; 5h, where L is the span of the element, h is the height of the section of the element. To determine the optimal arrangement of the reinforcing elements, computer simulation can be used, since excess reinforcement, in addition to a higher cost of the structure, can lead to brittle destruction of the masonry of the arch.

There are many methods for modeling vaults using various software. In computer simulation, researchers can consider masonry as a complex material (heterogeneous) consisting of elements of different stiffness (stone, mortar) or as a homogeneous structure. Both methods have their advantages, but the latter is preferable for tasks that describe large structures. Tasks are solved for flat (2D) or volumetric (3D) elements. Various numerical models are used. For example, in the work [17] for identical flat models, methods are compared: a Limit Analysis approach (LA), a FEM/DEM procedure and a non-linear heterogeneous Finite Element analysis (FE). With the works of Italian researchers, a flat homogeneous model is proposed in which bricks are considered as linear elastic elements [18]. A mesoscale description is employed for representing the heterogeneous behaviour of masonry units, mortar joints and brick-mortar interfaces, whereas a domain partitioning approach allowing for parallel computation is used to achieve computational efficiency in the work of the Tubaldi group on modeling arch bridges, taking into account damage to the masonry [19]. An extensive numerical investigation on the effect of TRM composites on the nonlinear response and failure modes of masonry walls presented in a study by Wang [20]. In the next article, to model the samples previously studied by Carozzi et al, we used the FE method in the 2D static analyses [21]. Predictions of active failure mechanisms, axial and breaking load lines in the absence and presence of TRM, SRG and FRP amplification are obtained. In some studies, when modeling reinforced masonry, the nonlinear work of both masonry and reinforcement elements are taken into account. [22]. This approach allows a more realistic description of the masonry destruction mechanism when using the FE method.

But in addition to the author’s modeling techniques, existing well-known software systems implementing the FE method are also widely used. To analyze the behavior of the vaults, software packages are needed that implement the finite element method and are focused on a wide range of construction tasks, for example, ANSYS or ABAQUS. Such complexes allow the simulation and calculation of the masonry model and reinforcement elements. So for a numerical study of the vault, damaged due to subsidence of the supports, and then strengthened by the FRCM system, the ABAQUS complex was used [23]. A heterogeneous model was used, calibrated against experimentally determined mechanical properties of materials. The results are close to experimental data.

However, it is difficult to simulate the masonry behavior with high accuracy.

2 Materials and methods

In this work, the modeling of brick arches on metal beams is performed in ANSYS PC. The construction model consists of three elements: steel beams, a brick arch and reinforcement material. I-beams are defined by finite elements of type Solid185 with the Mises strength criterion. The vault is
divided into volumetric finite elements of the Solid65 type with the William-Warnake strength criterion. The masonry is considered as a homogeneous element, which is a common practice in similar numerical studies [24]. When modeling the properties of masonry under load, the research of Kashevarova G.G. was taken as a basis, which describes field experiments to obtain complete diagrams of deformation (figure 1a). The experiments showed that the first cracks in the masonry appear at a load of 40-60% of the failure, which leads to a nonlinear nature of the deformation of the material. The strain diagram adopted in the simulation is shown in figure 1b.

![Strain Diagram](image)

**Figure 1.** The strain diagram: a) experimental by Kashevarova G.G., b) adopted in the simulation.

Composite reinforcement material is specified by finite elements of type Shell 181 with the Tsai-Wu strength criterion. To simulate the joint work of beams and brick filling of the arch, contact finite elements of the Target 170 and Contact 174 type were used with a friction coefficient of 0.8 and Bonded contact character (“connected”). Nonlinear calculation was performed by the Newton-Raphson method. The accepted characteristics of the model elements are shown in table 2.
Table 2. Characteristics of the model elements.

| Element           | FI type         | Density, kN/m² | E, MPa | G, MPa | v  |
|-------------------|-----------------|----------------|--------|--------|----|
| Masonry           | Solid/concrete  | 65             | 18     | 3000-600 | 0,1 |
| Steel beams       | Solid           | 185            | 78,5   | 170000 | 0,3 |
| Ruredil X Mesh c10 | Shell181        | 17.8           | (x) 240000 | (xy) 48000 | (xy) 0,25 |
|                   |                 |                | (y) 120000 | (yz) 3080  | (yz) 0,3  |
|                   |                 |                | (z) 120000 | (xz) 48000 | (xz) 0,25 |
| Carbon WrapTape 530/600 | Shell181  | 17.8           | (x) 245000 | (xy) 98000 | (xy) 0,25 |
|                   |                 |                | (y) 122500 | (yz) 5000  | (yz) 0,3  |
|                   |                 |                | (z) 122500 | (xz) 98000 | (xz) 0,25 |

The dimensions and characteristics of the elements of the vaults, the main defects are accepted according to the results of the survey of the "House Kiseleva" built in 1910, architect Oleshkevich. We studied a fragment of the basement overlapping with a span of five meters, with a beam spacing of a meter, a brick thickness of 120 mm, a boom of 120 mm, I-beams No. 16 of the German normal assortment with strength about 185 MPa, and the maximum strength of masonry elements is 3 MPa (for brick strength 10 MPa and mortar strength 5 MPa, respectively, which are definitely non-destructive methods).

A uniformly distributed load of 1 to 10 kN/m² with a step of 1 kN/m² until the virtual destruction of the structure was applied to the overlapping fragments. General view of the model is shown in figure 2.

During modeling, a possible increase in the load on the arch, deterioration of the physical and mechanical characteristics of the masonry (the decrease to 40% of the initial value in strength and elastic modulus), and a different arrangement of the reinforcing elements of two types are considered.

The reliability of the numerical simulation was evaluated by comparing it with the results of an experiment that showed good convergence.

At the first stage of the research the effect of various defects on the stress-strain state of arches was investigated. The influence on the bearing capacity of the arches of the following damage is considered: reduction of the supporting platform due to corrosion of the lower shelf of the carrier beam (taken into account by reducing the size of the lower shelf); the presence of a hole in the arch (a hole with dimensions of 500×500 mm is located in the middle of the span); decrease in masonry strength during variable freezing/thawing (from 20 to 80%; the combined effect of all damage).

In the next step, various amplification options are considered. From the experience of reinforcing structures, it is known that a different arrangement of reinforcing elements is possible, depending on the availability of the structure. During the modeling, the influence of different arrangement of
amplification systems was investigated: on the lower surface of arches and beams; on the upper surface of arches and beams; on both sides of the structure. The Ruredil X Mesh system was placed in a continuous layer, and the Carbon Wrap Tape system was discrete, with different strip directions. The considered options for placing the bands are shown in figure 3. The effect of the width of the carbon tape (150 mm and 300 mm) and its pitch from 100 to 300 mm on the bearing capacity of the reinforced arch is evaluated.

![Figure 3. The considered variants of placing a carbon ribbon.](image)

Next, an assessment was made of the strength and deformability of the reinforced vaults. For the strength methods, the hypothesis is accepted as the basis that the working scheme of a simple gentle arch can be represented as a system of independent parallel arches, where arches are a special case of the arch, its flat model.

If the load along the arch does not change, then its load-bearing ability and deformations can be judged by the work of one elementary arch of unit width, which is, therefore, the working scheme of the arch. However, a feature of the arches under consideration is the possible flexibility of their supports due to deformations of steel beams, which must also be taken into account in the calculation. Therefore, the algorithm for the calculation consists of two steps:

1. assessment of the bearing capacity and stiffness of the arch as a combined beam (main span of the ceiling), with the reduction of the elastic modules of the masonry and composite parts of the section to a common material – a steel beam, through reduction factors;

2. assessment of the bearing capacity of the masonry vault (before and after reinforcement) between the beams, the vault is considered as a hinged arch of unit width. Strength is determined in the middle of the span as for an eccentrically compressed element.

### 3 Results

As a result of numerical modeling, the nature of the stress distribution at each stage, the magnitude of the deformations, the crack-forming and destructive loads are established.

When varying the modulus of elasticity of the masonry for unreinforced samples, it was found that tensile stresses in the reference zones (0.15-0.18 L) for all loads exceed standard values, i.e. reinforcement of these zones is necessary. The compressive stresses in the masonry are up to 90% of the limit values. The stresses in the beams do not exceed the limit values, but the deflections are close to the
maximum allowable. The obtained dependences are shown in figure 4. When taking into account the development of corrosion in the lower flanges of the beams (reducing their cross-section), the deflections and stresses in the beams increase and reach limit values. Therefore, with such damage, reinforcement of the beams is necessary. The presence of a hole in the arch increases stresses in the beams by 5%, and compressive stresses in the masonry increase by a third. If steel beams are rigidly embedded in the walls, problems arise in their supporting zone, where stresses exceed the permissible values for almost all the defects considered, tensile stresses appear in arches near the walls, which is undesirable.

**Figure 4.** Dependencies obtained in the first series of studies:
a) Deflections in beams (Limit value 25 mm); b) Stress in beams (Limit value 185 MPa); c) Stress in masonry (Limit value is 50% from Ultimate stress).
The nature of the stress distribution and the appearance of cracks in the unreinforced sample without damages are shown in table 3. The presence of defects significantly affects the magnitude of the stresses and deformations of the arches; and a combination of several defects leads to excess values, i.e. reinforcement of such structures is required. As can be seen from table 3 masonry destruction begins at mid-span at the bottom section at loads of about 50% of the failure. With further increasing load, cracks develop substantially the entire bottom surface of the arch, except the support and appear in zones of the compressed part of the section. Concentration before failure occurs in the middle third damage span arch, which agrees well with findings of other researchers. Failure occurs on normal section.

Table 3. The nature of the stress distribution for an unreinforced arch without defects depending on load changes (per 1 to 6 kN/m²).

| Stress distribution, MPa | Cracking |
|-------------------------|---------|
| ![Stress Distribution](image1.png) | ![Cracking](image2.png) |
| ![Stress Distribution](image3.png) | ![Cracking](image4.png) |
| ![Stress Distribution](image5.png) | ![Cracking](image6.png) |
| ![Stress Distribution](image7.png) | ![Cracking](image8.png) |
| ![Stress Distribution](image9.png) | ![Cracking](image10.png) |
| ![Stress Distribution](image11.png) | ![Cracking](image12.png) |
| ![Stress Distribution](image13.png) | ![Cracking](image14.png) |
| ![Stress Distribution](image15.png) | ![Cracking](image16.png) |
| ![Stress Distribution](image17.png) | ![Cracking](image18.png) |

The analysis of similar patterns for a vault with defects showed that even with a minimum load, cracks appear from the support zones, the masonry works for shearing. In the next step, the loads of cracks are distributed over the entire lower surface of the arch and develop into a depth of more than half the section. Further, cracks continue to develop throughout the arch, but their concentration is distinguished in the zone of the inclined section, along which fracture occurs.

For vaults reinforced with a carbon tape from the bottom, the appearance of local damage in the middle of the span and micro damage in the area of the supports was established. The development of damage is less intense compared to non-reinforced arches. The maximum stress concentration is observed at a third of the span from the support, where the destruction occurs. According to the study results, it is worth noting that the destruction of all the structures under consideration occurs along the masonry, that is, ultimate stresses occur earlier in brick than in beams. The crack-forming and destructive loads are shown in table 4. It was found that the greatest effect is achieved by the Carbon Wrap system, and the use of individual bands makes this solution economically advantageous.
When reinforcing with a carbon tape from above, damage was found to occur mainly along the upper surface of the arch, with further development over the entire height of the section. Damage is concentrated mid 2/4 span. The destruction occurs from the fragmentation of the upper part of the vault.

When reinforced on both sides, the nature of the damage is at first similar to the previous case. However, as the load increases, damage covers approximately 3/5 of the span. Before destruction, almost the entire brick body of the vault is damaged.

| Vault scheme option                        | \(q_{crs}, \) kN/m² | \(q_{ult}, \) kN/m² |
|--------------------------------------------|----------------------|----------------------|
| Without defects                            | 3                    | 6                    |
| With defects (masonry strength during to 40%) | 1                    | 4                    |
| defective vault reinforcement by Ruredil X Mesh C10 |                      |                      |
| solid bottom                               | 1                    | 4                    |
| solid top                                  | 3.5                  | 7                    |
| solid both sides                           | 3.8                  | 8                    |
| defective vault reinforcement by CarbonWrap |                      |                      |
| local bottom                               | 3                    | 6                    |
| local top                                  | 4                    | 9                    |
| local both sides (base sheme)              | 4.6                  | 10                   |

It can be pointed out that when using carbon tape, the brick part of the cross-section of the arch is quickly excluded from work due to delamination into individual fragments held only by reinforcing elements.

4 Discussion
The most dangerous for the arch is a decrease in masonry strength due to soaking and a significant increase in load.

The option and system of amplification affects the nature of the stress distribution in the material of the arch, however, in steel beams, the nature of the stress distribution does not change. It was found that the greatest effect is achieved by the CarbonWrap system, and the use of individual bands makes this solution economically advantageous.

Among the options for arranging strips of different sizes, the most effective solution was reinforcing with ribbons 150 mm wide in increments of 100 mm. According to the calculation results, the maximum reinforcement efficiency – an increase in the bearing capacity by 2 times is achieved when the masonry strength is reduced by no more than 40%, at 60% the breaking load increases by 1.57 times, at 80% – 1.25 times.

The arrangement of reinforcing elements also significantly affects the fracture toughness and bearing capacity of the arches. When positioned below, the Ruredil X Mesh C10 system is inefficient, and Carbon Wrap restores the characteristics to an intact element. When placed on top, the first of the systems increases crack resistance by 3.5 times, and the strength by 1.75 times, exceeding the performance of an intact structure, the second system is 4 times and 2.25 times more effective, respectively. The maximum increase in performance is achieved with a combined arrangement of amplification. However, from the point of view of economic efficiency, local strengthening is more attractive – for example, in the lower part only gluing along the beams with an institution on the supporting zone of the arches.

The results obtained by the proposed method for calculating the arch as a combined beam for the Carbon Wrap carbon tape reinforcement option were compared with the results in ANSYS and showed a discrepancy of less than 10%, table 5.
Table 5. Maximum stresses and deflections in a steel beam.

| Results                | $\sigma_{\text{bottom}}$ MPa | $\sigma_{\text{top}}$ MPa | Deflection, mm |
|------------------------|-----------------------------|---------------------------|-----------------|
| ANSYS PC               | 136.4                       | 98.75                     | 18.6            |
| Proposed method        | 144.6                       | 97.95                     | 16.6            |
| Discrepancy            | 5.7%                        | 0.77%                     | 10%             |

Sticking reinforcement elements on masonry using epoxy glue can affect the vapor permeability of the masonry, reducing the strength and deformation characteristics of the lime masonry mortar. For vaults inside buildings, the problem is solved by the proper organization of the microclimate of the premises. For external structures, the vapor permeability of the reinforced structure is determined by the calculation, which determines the minimum allowable pitch of the reinforcing elements.

Analysis of verification calculations showed that in our case, the material of the arches has a large margin of safety, and in steel beams the stress and strain exceed the permissible values with increasing load. Therefore, reinforcement is necessary specifically for beams, which determines the use of carbon ribbons located along the elements. If the bearing capacity of the beams is sufficient, and the strength characteristics of the masonry substrates do not meet the requirements of the standards, it is better to reinforce with a solution reinforced with a non-metallic mesh. Non-metallic meshes are mandatory for outdoor structures to prevent cold bridges. The Ruredil X Mesh system is optimal for damage, such as soaking, or a large number of small cracks. Its maximum efficiency is achieved with the device from above, increasing the bearing capacity up to 30%.

However, when assessing the strength of the arch between the beams, a significant discrepancy between the results obtained indicates the need for a fundamentally different approach to assessing the strength of the arch. A physical experiment is required that will establish the actual spatial work of the elements.

5 Conclusions
1. The effectiveness of using the proposed amplification schemes must be verified by comparison with a physical experiment.
2. Vaults without defects do not require reinforcement.
3. Reinforcing with carbon tapes in case of masonry damage in the form of soaking and small cracks is not economically feasible, the use of reinforced mortar (FRP) is recommended.
4. In case of insufficient bearing capacity of steel beams, it is recommended to use carbon tapes, bearing capacity maximally increases 70%.

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