Reinforcement of brick structures with carbon fiber

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Abstract. Based on the analysis of approaches to reinforcing the brick masonry structures, the advantages of carbon fiber as a reinforcing component are presented. Methods for calculating brick structures reinforced with carbon fiber under central and eccentric compression are proposed. These methods allow determining the longitudinal force taking into account the calculated compressive resistance of the masonry, the masonry working conditions and the influence of long-term load, as well as the coefficient of the masonry surface reinforcement at the reinforced wall. The schemes of strengthening the wall with vertical canvases and at the same time vertical and horizontal carbon fiber canvases are considered. Depending on the direction of the eccentricity of the load application, methods for calculating the strength of reinforced masonry under the action of a moment in the masonry plane and from the wall are developed. The ultimate deformations of carbon fiber are estimated taking into account possible options for the destruction of masonry reinforcing elements.

1. Introduction
Over the past 10-15 years, the volume of reconstruction work, including restoration and major overhaul, of buildings for various purposes has significantly increased in order to extend the life cycle of existing objects and bring the building structures in accordance with the requirements of modern regulatory documents in terms of strength [1].

The problem of increasing the strength of brick structures is more urgent than ever in the case of strengthening the existing structures, during the reconstruction of old buildings in connection with their superstructure, increased load on structures, due to physical deterioration of structures, the appearance of defects and damages associated with technological processes or mechanical effects on structures. If the design of buildings and structures this problem is solved by using high-strength materials [2], then during the reconstruction – by using metal or reinforced concrete cages.

Known solutions to improve the mechanical characteristics of bricks masonry include the search for new mortar compositions [3], strengthening with fiber-reinforced polymers and various organic materials [4, 5], development and implementation of textile reinforced mortar [6, 7] and others. In particular, reinforcing the brickwork with 25 mm sisal fibers added to the mortar allowed to increase the allowable vertical load resistance from 40 kN/m to 100 kN/m [8]. It was shown in [9] that the use of a textile-reinforced mortar changes the energy dissipation capacity of the masonry structure and allows during restoration work not only to completely restore the building's original bearing capacity, but also to increase it by more than 25% compared to as-built case.
Compared with other methods of reinforcing masonry, fiber reinforcement is distinguished by the convenience of technical implementation, economy and high rehabilitation effect. Reinforcing fiber prevents the destruction of the cement mortar during loading and increases the overall ductility of the brickwork. Steel fibers, as well as various natural and synthetic fibers, are widely used in the global construction industry for these purposes [10-12]. Carbon fibers are an effective alternative to traditional fittings, because they are lightweight, have high tensile strength and elastic modulus, and also do not cause corrosion [13].

Composite reinforcement is most justified for application where it is necessary to ensure reliable operation of structures, first to reinforce unique, historically important structures, dismantling and replacement of which is much more expensive than repair or is impossible at all. This applies both to architectural monuments and to ordinary structures. Composite materials made of carbon fiber have high tensile strength, corrosion resistance, there are no dimensional restrictions that limit their use; besides, complex work and equipment are not required [14]. Mechanical characteristics of external reinforcement elements [15] vary within the following limits: \(E = 76-340\) GPa, \(R = 1300-4900\) MPa.

Carbon fiber consists of polyacrylonitrile that has been pre-treated with high temperatures (up to 3-5 thousand degrees) [16]. Due to technical features, carbon fiber is used for external reinforcement, in the process of which it is impregnated with a binder (two-component epoxy resin) and glued to the surface of the structure it is where it is needed. The usefulness of this binder has been proven in several ways: first, the epoxy resin has high adhesion to various materials; second, after chemical reaction with the resin, the carbon fiber is converted into rigid plastic, obtaining high strength.

The carbon composite material’s long service life is caused by a combination of the following advantages [17]:

1) high waterproofing characteristics due to the glossy surface of the carbon plastic, whereby the material does not react with water;
2) sufficient corrosion resistance;
3) lightness (property due to which the reinforcement system does not create additional loads on the structures);
4) environmentally friendly and toxically safe material;
5) refractoriness and impact resistance.

The relevance of this study proves the fact that reinforcement with composite materials is a less time-consuming process [18] compared to reinforced concrete and metal cages. In addition, it should be noted that carbon fiber is a durable material and has good endurance [19]. However, it should be noted that the published works on this subject are mainly empirical and many issues of numerical modeling remain unresolved, in particular, the calculation of masonry structures reinforced with carbon fibers.

The purpose of this work is to develop a technique for calculating carbon-reinforced brick masonry structures to assess their load-bearing capacity at central and eccentric compression, and also the calculation of the strength of reinforced masonry under the action of the moment in the masonry plane and in the wall plane.

2. Methods

2.1 The method of calculation of brick structures, reinforced with carbon fiber at central compression. Based on the calculation methods by standard "Stone and Reinforced Stone Structures. The Updated Edition" and "Design of Stone and Reinforced Stone Structures", we propose to calculate the elements of brick structures under central compression, reinforced by external reinforcement made of composite materials, by the formula:

\[ N \leq m_1 \cdot m_2 \cdot \varphi \cdot R_d \cdot A \]  

where \(N\) – calculated longitudinal force;
R_{rf} – calculated compression resistance of the masonry, reinforced with external reinforcement of composite materials and determined by the formula:

\[ R_{rf} = R + \rho \cdot \mu \cdot \frac{R}{100} \leq 2 \cdot R \]  \hspace{1cm} (2)

where \( R \) – calculated compression resistance of the masonry, determined by standards;
\( \varphi \) – buckling coefficient, determined by standards;
\( A \) – sectional area of element;
\( m_g \) – the coefficient, taking into account the effect of a long load;
\( m_k \) – the coefficient of masonry working conditions (for masonry without damage equal to 1, with damage \( \leq 0.7 \));
\( \rho \) – the coefficient, taken with a void of brick (stone) up to 20% inclusive – 2, with a void from 20% to 30% inclusive – 1.5, with a void above 30% – 1;
\( \mu \) – the coefficient of surface reinforcement with composite masonry material of reinforced wall:

\[ \mu = \frac{S_{bd}}{S_w} \cdot 100 \]  \hspace{1cm} (3)

\( S_{bd} \) – the sectional area of strip (bands) of composite material with thickness \( \delta_{bd} \) and height \( h_{bd} \), determined by formula (Fig. 1):

\[ S_{bd} = 2 \cdot \delta_{bd} \cdot h_{bd} \]  \hspace{1cm} (4)

\[ S_w = h_u \cdot (h_{bd} + b) \]  \hspace{1cm} (5)

\( R_t \) – calculated tensile strength of a composite material, determined by a formula:

\[ R_t = \frac{R_{t,x}}{\gamma_t} \]  \hspace{1cm} (6)

\textbf{Figure 1.} Brick pillar amplification scheme.
where \( R_{f,n} \) – tensile strength of the composite material;
\( \gamma_f \) – the reliability coefficient for composite material, taken when calculating the limit states of the second group equal to 1.0, and when calculating the limit states of the first group equal to 1.2 for unidirectional carbon tapes and 1.8 for bidirectional carbon fabrics.

When the fabric label is applied in a “wet” way (a preproofed fabric is glued to the adhesive layer), the values of the reliability coefficient \( \gamma_f \) is increased by 15%.

When calculating by limit states of the first group, it is allowed to accept the value of reliability coefficient \( \gamma_f \) for laminates according to manufacturer’s data, but not less than 1.1.

2.2 The method of calculation of brick structures, reinforced with carbon fiber at eccentric compression

Calculation of eccentrically compressed unreinforced elements of stone structures reinforced with external reinforcement from composite materials (Fig. 2) is proposed to perform according to the formula:

\[
N \leq m_k * m_g * \varphi_1 * R * A_c * \omega
\]

where \( A_c \) – the area of the compressed part of the section at rectangular stress distribution;
\( R \) – the calculated compression resistance of the masonry;
\( \omega \) – coefficient, determined by standard "Stone and reinforced stone structures";
\( m_k \) – coefficient of masonry working conditions (for masonry without damage equal to 1, with damage – 0.7);
\( m_g \) – the coefficient, determined by standards "Stone and reinforced stone structures";
\( \varphi_1 \) – coefficient, determined according to equation:

\[
\varphi_1 = \frac{\varphi + \varphi_c}{2}
\]

where \( \varphi \) – the buckling coefficient, for the entire section in the plane of action of the bending moment, determined by the calculated height of the element by standard "Stone and Reinforced Stone Structures";
\( \varphi_c \) – the buckling coefficient, for the compressed part of the section, determined by the actual height of the element \( H \) according by standard "Stone and Reinforced Stone Structures" in the plane of action of the bending moment in relation.

\( m_g, \varphi_1, R, A_c, \omega \) – parameters determined according to the standard "Stone and Reinforced Stone Structures".
Figure 2. Eccentric compression and alternating bending moment diagram for an eccentrically compressed element.

In the case of an alternating bending moment diagram by the height of the element (Fig. 2), the strength calculation should be done in sections with the maximum bending moments of different signs. When calculating the eccentric compression of stone partitions or walls depending on eccentricity direction of load application two schemes should be considered: moment actions in plane and from the masonry plane.

3. Results and discussion
3.1 Calculation of the strength of reinforced masonry under the action of the moment in the masonry plane

Calculation of the strength of reinforced masonry under the action of the moment in the masonry plane is made from the condition:

\[ M = M_n \]  \hspace{1cm} (9)

\[ M_n = \sum F_i \cdot \left( d_i \cdot \frac{\beta_1 \cdot c}{2} \right) + N \cdot \frac{L}{2} - \frac{\beta_1 \cdot c}{2} \]  \hspace{1cm} (10)

where \( d_i \) – the distance to the middle of the composite strip (Fig. 3);
\( \beta_1 \) – the coefficient of reduction of the stress distribution to a rectangular one, is taken to be equal to 0.7;
\( F_i \) – direct stress, that falls on the i-th composite strip;
\( P_u \) – the value of vertical load on the calculated masonry section;
\( L \) – the length of the calculated masonry elements;
\( c, t \) – sizes of the compressed zone.

Figure 3. Scheme of strengthening the wall with vertical canvases.

Calculated horizontal force on the masonry, corresponding to \( M_n \), we determine by the formula:
where \( h_f \) = \( \ell_f \times k \) (see Fig. 3);

\( k \) – the coefficient of working conditions of the carbon fiber reinforcement layer, accepted by equal 0.6 for one-way reinforcement and 0.45 for two-way reinforcement.

If it is necessary to reinforcing the masonry under the action of horizontal force and bending moment, it is possible to use a reinforcement schemes with vertical and horizontal canvases (Fig. 4). At the same time, separate calculations are made for the effect to horizontal load and moment in the masonry plane [20].

3.2 Calculation of masonry under the action of the moment from the wall plane.

When calculating the masonry for the action of the moment from the wall plane, the following design assumptions are accepted:

- stresses in carbon fiber are directly proportional to their distance to the zero line;
- maximum relative deformation of the masonry mortar – 0.0025, of the brick – 0.0035;
- carbon fiber works linearly until reaching the maximum load;
- the work of masonry in tension, and carbon fiber in compression is not taken into account;
- there is no carbon fiber slipping over the masonry;
- under h/t less than 0.8, the bending of the wall from the plane should be neglected [21].

Calculation of reinforced masonry strength at action of moment from masonry plane is performed on condition:

\[
Q_t = \frac{M}{h_f}
\]  

(11)

where \( h_f = \ell_f \times k \) (see Fig. 3);

\( k \) – the coefficient of working conditions of the carbon fiber reinforcement layer, accepted by equal 0.6 for one-way reinforcement and 0.45 for two-way reinforcement.

3.2 Calculation of masonry under the action of the moment from the wall plane.

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- there is no carbon fiber slipping over the masonry;
- under h/t less than 0.8, the bending of the wall from the plane should be neglected [21].

Calculation of reinforced masonry strength at action of moment from masonry plane is performed on condition:

\[
M = M_n
\]  

(12)

\[
M_n = A_t^*R_{fc} \left( \frac{t}{2} - \frac{\beta_1^*c}{2} \right) + P_a^* \left( \frac{t}{2} - \frac{\beta_1^*c}{2} \right)
\]  

(13)

where \( R_{fc} \) – the effective stress in carbon fiber canvases taking into account the value of the limit strain on the contact “canvas – masonry material” is determined by the formula:
Taking into account possible variants of deterioration of the masonry reinforcement element by composite material (deterioration of the masonry during compression, separation of carbon fiber canvases from masonry), the limit deformations of carbon fiber are limited by the following dependence:

\[ \varepsilon_{\text{fe}} = \varepsilon_{\text{mu}} \left( \frac{1 - C_e}{C_e} \right) \leq \min \left( k \varepsilon_{\text{mu}}^* C_E \varepsilon_{\text{mu}}^* \right) \]  

(15)

where \( \varepsilon_{\text{fe}} \) – calculated tensile deformation;
\( C_E \) – the coefficient of working conditions, taking into account the impact of the environment (equal to 0.9 for internal room and 0.8 for the willing structures and structures in an aggressive environment);
\( \varepsilon_{\text{mu}}^* \) – ultimate strain abruption of the canvas is determined by the passport data on the composite material.

The proposed calculating techniques take into account the features of reinforced brick masonry structures and the properties of the materials used, and allow to assess their load-bearing capacity at central and eccentric compression, and also the calculation of the strength of reinforced masonry under the action of the moment in the masonry plane and in the wall plane.

4. Conclusions
Based on a comparative assessment of the traditional methods of reinforcing brick structures with the carbon fiber reinforcement method, the advantages of fiber-reinforced masonry structures are shown.

A technique for calculating carbon-reinforced brick masonry structures to assess their load-bearing capacity at central and eccentric compression has been developed. New technique allows us to calculate the values of the longitudinal force from the calculated compressive resistance of the brick masonry with external carbon fiber reinforcement.

Equations are proposed for calculating the reinforced masonry under the action of a moment in the masonry plane and from the wall plane.

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