Reinforcement of reinforced concrete structures with composite materials

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Abstract. Composite materials are becoming more widespread in many areas of the national economy, including in construction, due to their high strength parameters with low weight characteristics. Currently, composite material is the most promising material in building. The use of composite materials in construction for the manufacture, reinforcement and repair of reinforced concrete structures facilitates their lightening, allows varying the physical and mechanical characteristics by positioning the composite base in the desired direction. Therefore, consideration of the issues of reinforcing floor slabs commonly used in construction with composite materials is an important and relevant topic. The use of composite materials in reinforced concrete elements provides increased crack resistance and stiffness of reinforced concrete elements. This is due to the localization and redistribution of deformations in the stretched zone.

1. Introduction
Consider the recommendations and standards developed in Russia for the use of composite material in reinforced concrete structures, these include:

- One of the main works on the design, manufacture and analysis of structures using composite materials is the work of the Research and Development Institute of Concrete and Reinforced Concrete [1].
- Guidelines for strengthening reinforced concrete structures with composite materials [2];
- Organization standard "Reinforcement of reinforced concrete structures with composite materials" [3];
- Recommendations for calculating the reinforcement of reinforced concrete structures with a system of external reinforcement made of polymer materials [4];
- Guidelines for the reinforcement of reinforced concrete structures with composite [5].

The above materials take into account the experience gained in Russia and abroad in the use of composite materials to strengthen reinforced concrete structures in construction. Methods and approaches to solving this problem are presented. Typical and design characteristics of homogeneous and composite materials. Calculations of the stress-strain state of concrete structures reinforced with composite materials in linear and nonlinear formulations. Recommendations for the placement of composite structures are given depending on the stress-strain state of the structure and the acting loads. One of the methods of reinforcing reinforced concrete structures is to change the structural scheme with additional structures that redistribute the acting loads to less loaded elements. This method is called the method of summing up the unloading structure, consisting of frames, support posts, puffs,
beams, etc. The connection of the unloading structure makes it possible to reduce the span of the bearing elements and to increase the bending stiffness. Reinforcement without bringing the unloading structure is carried out by gluing reinforcing elements made of sheets composite materials to the structure. Such reinforcement is carried out by positioning the composite material in the zones of greatest stress.

In addition, the use of reinforcing bars made of composite material instead of metal reinforcement in reinforced concrete structures is recommended in reinforced concrete structures operating in conditions with high humidity and in conditions conducive to the ingress of water into cracks, for example, bridges, overpasses. The most commonly used composite materials for reinforcing reinforced concrete structures are composite materials based on carbon fibers, which have high tensile-compression characteristics and an elastic modulus close to that of steels. The use of glass and aramid fiber reinforcement, due to the low modulus of elasticity, requires a thicker outer reinforcement layer. This approach leads to the need to take into account large shear stresses at the interface between concrete and external reinforcement with structures of composite materials in order to work together.

To connect the composite material with a concrete base, the following types of epoxy materials are used:

- Primer for impregnating and strengthening the surface layer of the concrete base
- Putty for filling small uneven surfaces of concrete
- Adhesive (adhesive) compositions for joining composite canvases with a concrete base.

For the joint work of concrete and composite, a special anchoring or bending of the composite layer to the adjacent plane is sometimes used.

Water ingress into reinforced concrete structures leads to corrosion of concrete and reinforcement. Composite materials are not susceptible to corrosion, therefore, the consideration of the use of composite material in reinforced concrete structures, the development of methods for calculating concrete structures with a composite structure is an important and urgent topic.

Consider the work on the use of reinforcing reinforced concrete structures with composite materials.

In work [5] the author sets out in detail the problems, methods of solution of reinforced concrete structures, gives recommendations for strengthening and repairing reinforced concrete structures. Detailed calculations of the considered structures are given. Recommendations are given on the location and parameters of the reinforcing elements.

One of the main works on the description and study of reinforced concrete structures is the work of A.G. Tamrazyan. [6], which discusses methods and approaches for the design, calculation and manufacture of reinforced concrete structures.

In [7], the use of composite reinforcement in reinforced concrete structures is considered. The development of the theory of calculation of structures with composite reinforcement is given. In the considered reinforced concrete structure, the composite reinforcement element is connected to the reinforced concrete structure using an adhesive with inelastic properties. The main factor affecting the reliability of the structure is the adhesion of the composite reinforcement with concrete. For the efficiency of the structure, the joint operation of the reinforcement element and the main reinforced structure is necessary, which is achieved by taking into account the shear deformation in the contact connection. The article discusses experimental studies of reinforced concrete structures with external reinforcement of various types of composite materials. Reinforced concrete beams with A500 class reinforcement and A600 class reinforcement were used. The prototypes of the beams were reinforced with canvases made of fiberglass and carbon fiber, and carbon laminates.

The work [8] considers the design and methods of reinforcing reinforced concrete structures with composite materials based on carbon, aramid and glass fibers. Approaches to the calculation of reinforced concrete structures reinforced with composite materials for the limiting state of the first group and the limiting state of the second group are presented. New approaches for reinforcing reinforced concrete with composite materials and technologies for their implementation are presented.
The book [9] contains extensive material on the use of composite materials in reinforcement with composite materials. The generalization of the considered calculation methods is carried out. Recommendations on the use of composite material in reinforced concrete structures are given.

In article [10] the study of external reinforcement with composite materials of reinforced concrete structures is presented.

The works [11-13] of foreign authors and Russian scientists consider methods and methodologies, as well as experimental materials on the use of composite materials in construction. On the use of reinforcement of reinforced concrete structures with polymer and composite materials.

The work [14] is devoted to the material-oriented use of composites in bridge building and construction.

The work [15] provides guidance on the design and construction of FRP systems with an external connection to strengthen concrete structures.

The work [16, 17] considers the design of composite steel and concrete structures. General rules and regulations for the use of composite materials in construction.

Article [18] provides standard specifications for reinforced thermosetting plastic poles used in Pennsylvania, USA.

Article [19] provides guidance on the design and construction of external coupled FRP systems to reinforce existing structures.

In [20], models for the longitudinal shear strength of composite slabs and the use of non-standard test data are considered when using composite structures in steel and concrete.

In article [21] composite slabs and beams using steel deck are considered. The best practices in design and construction of the use of composite structures in construction are taken into account.

The article [22] considers the problem of joints in a steel structure made of composite material.

In work [23], the stress-strain state of a concrete beam reinforced with fiberglass reinforcement is investigated.

In article [24], the calculation of reinforced concrete slabs with their reinforcement with composite materials is carried out.

The work [25] is devoted to the consideration of structures made of reinforced concrete and concrete. Regulatory rules for the design of concrete structures reinforced with composites are considered.

The article [26] examines the modeling of the bond between laminated CFRP strips located near the surface and concrete.

The article [27] considers fiberglass reinforcement for concrete structures.

The article [28] presents the results of reinforcing reinforced concrete floor slabs with carbon composite materials.

The above works show that considerable attention is paid to the issues of strengthening and using composite materials in reinforced concrete structures, at the same time, a large number of parameters affecting the strength and stiffness characteristics of composite materials require further study of this problem.

The issues of calculating concrete structures with composite reinforcement receive attention not only in theoretical and experimental studies. Computer-aided design systems have also drawn attention to this problem.

In LIRA-2018 the calculation is implemented of non-metallic composite basalt reinforcement. When calculating the reinforcement, the following classes of non-metallic composite basalt reinforcement ANPB 800 and ANPB 1000 are used, which can only be used as longitudinal reinforcement. In this case, steel reinforcement is used as transverse.

The program implements the calculation of non-metallic composite basalt reinforcement for the following types of standard sections: timber, I-beam, box, ring, circle, cross, corner sections. Also, the calculation of composite basalt reinforcement for plate elements: shells, slabs, beams-walls is implemented. A stress-strain analysis of a reinforced concrete structure with composite reinforcement according to SP 63.13330.2012 has been implemented.
The solution of problems with the use of a composite material is considered in most modern computer-aided design systems, since at present such a material is the most promising with a high specific strength, which makes it possible to design physical and mechanical characteristics depending on the location of the layers of a multilayer composite structure.

2. Main part

The use of a multilayer composite material, with a different arrangement of the base in the layers of the composite, requires the calculation of its characteristics. There are two approaches to calculating a multilayer composite material. In the general case, it is fashionable to write the relationship between efforts and deformations as:

\[
\begin{pmatrix}
N \\
M
\end{pmatrix} = \begin{pmatrix}
A & B \\
C & D
\end{pmatrix} \begin{pmatrix}
\varepsilon \\
\chi
\end{pmatrix}.
\]

Here is designated \( N \) – are the membrane forces, \( M \) – are the bending moments.

\[
(A_{ij}, B_{ij}, D_{ij}) = \int_{-h/2}^{h/2} \overline{Q}_{ij}(1, z, z^2) \, dz, (i, j = 1, 2, 3).
\]

Denoted here

\[
A_{ij} = \sum_{k=1}^{n} \overline{Q}_{ij}(h_k - h_{k-1}), i, j = 1, 2, 6, \quad B_{ij} = \sum_{k=1}^{n} \overline{Q}_{ij}(h^2_k - h^2_{k-1}), i, j = 1, 2, 6,
\]
\[
D_{ij} = \sum_{k=1}^{n} \overline{Q}_{ij}(h^3_k - h^3_{k-1}), i, j = 1, 2, 6, \quad Q_{11} = E_s/(1 - \nu_s\nu_{s\theta}), \quad Q_{12} = \nu_sE_s/(1 - \nu_s\nu_{s\theta}), \quad Q_{21} = \nu_{s\theta}E_s/(1 - \nu_s\nu_{s\theta}), \quad Q_{22} = E_{\theta}/(1 - \nu_s\nu_{s\theta}), \quad Q_{66} = G_{66}.
\]

\[
\overline{Q}_{11} = c^4Q_{11} - s^4Q_{22} + 2(Q_{12} + 2Q_{66})s^2c^2, \quad \overline{Q}_{12} = (Q_{11} + Q_{22} - 4Q_{66})s^2c^2 + (s^2+c^2)Q_{22},
\]
\[
\overline{Q}_{16} = (c^2Q_{11} - s^2Q_{12} + (Q_{12} + 2Q_{66})(s^2-c^2))sc, \quad \overline{Q}_{22} = s^4Q_{11} - c^4Q_{22} + 2(Q_{12} + 2Q_{66})s^2c^2,
\]
\[
\overline{Q}_{26} = (s^2Q_{11} - c^2Q_{12} - (Q_{12} + 2Q_{66})(s^2-c^2))sc, \quad \overline{Q}_{66} = (Q_{11} - 2Q_{12} + 2Q_{22})s^2c^2 + (s^2-c^2)Q_{66}.
\]

The designations in the formula (1) are shown in figures 1, 2.

![Figure 1. Multilayer composite structure](image)

Consider a three-layer composite structure consisting of external load-bearing layers and a layer filled with them. A core layer consisting of a foam-type material only absorbs shear stresses and prevents the bearing layers from coming together (figure 3).

The displacement of the neutral layer of a three-layer composite structure is determined from the relations,

\[
u_o = (\bar{u}_1 + \bar{u}_2)/2, \quad \varphi_o = (\bar{u}_1 - \bar{u}_2)/h_3, \quad \bar{u}_1 = u_1 - h_1 e_{13}/2, \quad \bar{u}_2 = u_2 + h_2 e_{23}/2
\]

where \( u_1 \) and \( u_2 \) displacement of the bearing layer and the angles of rotation \( \varphi_1 \) and \( \varphi_2 \), the thicknesses are indicated as \( h_1 \) and \( h_2 \). Through \( u_o \) designate the displacement of the middle layer and \( \varphi_o \) the angle of rotation, expressed through the generalized characteristics of the bearing layers.
Figure 2. Three-layer composite structures

The characteristics of a multilayer composite material largely depend on the location of the composite substrate in the layer. To ensure maximum rigidity of the multilayer composite material to the structure, it is necessary to locate the base of the composite material along the lines of maximum stresses. Therefore, the arrangement of the base of the composite material in layers is as follows:

- Calculation of a structure made of a homogeneous material is carried out
- Trajectories of maximum stresses are determined
- We place the basis of the compositional material along the lines of the obtained maximum stresses
- Correcting the location of the base of the composite material according to the results of calculating the structure of the composite material

3. Results

The calculation of a three-layer slab consisting of external composite bearing layers with a thickness of 25 mm and a thickness of an inner layer of 200 mm has been carried out. A uniformly distributed load is applied to the floor slab (permissible operational load on reinforced concrete floor slabs) 800 kg/m². In the calculations, a floor slab restrained along the contour was considered.

The calculation was carried out numerically using the finite element method. The convergence of the calculation results was checked by increasing the number of finite elements.

The dimensions of the floor slab: length 6 m, width 1.5 m. As a result of the calculation, the stress-strain state of a three-layer composite plate was determined. The stock of strength turned out to be more than 3, the maximum displacement was 6.5 mm.

Figure 3. Calculation of a three-layer composite slab
4. Conclusions
A review of the literature has shown that the problem of strengthening building structures has received considerable attention in the literature and real construction. Therefore, calculations related to the reinforcement of floor slabs with composite canvases are important and relevant work. Calculations have shown that the use of composite canvases to strengthen the structure in the zone of tensile stresses makes it possible to obtain workable floor slabs that can be used during the operation.

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