Numerical Solutions and Experimental Research in Justification of the Design Model of the Force Interaction of the Reinforcing Beam with the Anchoring Medium

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Abstract. The paper presents the research and engineering experience in the calculation and design of concrete structural elements, reinforced by fiberglass rods. The construction of a concrete beam reinforced by fiberglass rods is presented. Research in preserving prestressing forces in a beam subjected to weathering for about 30 years is considered. The creation and analysis of concrete-steel connection model is presented using LIRA-SAPR software. This is a work of scholarly interest.

1. Introduction

The experience of using non-metallic composite materials is quite large in foreign countries. In addition, it is systematized into a single database. There are uniform regulatory documents on the calculation and design of structures with non-metallic composite materials.

In Russia, this issue has been actively discussed only in the last decade. Non-metallic composite reinforcement has both advantages and disadvantages that do not allow it to be widely used in structures.

Active researchers of non-metallic low-modulus reinforcements embedded into concrete matrix are professors T. Lin, N.P. Frolov, V.I. Kulish. In his monograph [1] T. Lin notes the rational use of fiberglass reinforcement (in the prestressed condition), the creation of effective anchor devices for low-modulus reinforcement and the protection of fiberglass reinforcement in an alkaline environment.

Professor Vladimir Ivanovich Kulish successfully engaged in the development of workable anchor and gripping devices for low-modulus composite reinforcement [2]. The experimental spans were designed and mounted under his leadership [3].

The research object of this paper is modeling the bond between composite reinforcement and external matrix, which can be concrete, polymer concrete, etc.

2. Production of prototypes. The results of experimental sampling analysis
A fiberglass concrete beam, made in 1987 under the direction of V.I. Kulish, was taken for laboratory experimental studies [14]. After manufacturing, the beam was taken outside and exposed to the environment for 30 years.

Fiberglass concrete T-beam, 5 m full length, 4.6 m design span. Beam height 33.5 cm, slab width 18.5 cm, thickness 4.5 cm. The web is made in the form of a trapezoid with an average thickness of 8 cm.

The beams were reinforced with tensile reinforcement (FRP rebar) Ø 6 mm and flat frames made of A-I class steel rods, Ø 5 mm. There were 6 FRP rods in each beam, the beam design is shown in Figure 1.

![Figure 1. The design of fiberglass concrete T-beam.](image1)

Flat meshes SP and SR were used as nonprestressed reinforcement, installed respectively in the slab and web. In addition, open stirrups were installed.

Bundles of 6 rods Ø 6 mm, 600 cm long were used for preliminary pressing of the experimental fiberglass concrete beam.

The external anchor at the dead end of the stand was a pipe ferrule Ø 60 mm, 260 mm long with FRP rods inserted into it and filled with an epoxy compound of the following composition: ED-5 epoxy resin - 100 phr, polyethylene-polyamine - 15 phr, quartz sand - 100 phr, portland cement - 100 phr.

Anchoring of FRP rods at the expansion end of the stand was carried out using an anchor - gripping device with crimp plates according to patent No. 576374.

The position of the internal anchors is shown in Figure 2.

![Figure 2. The layout of the internal anchors.](image2)

The internal anchor according to [4] is made in the form of a prism of aluminum alloy. A piece of soft wire is passed through a prism and wire ends are twisted on bundled FRP beams, stabilizing the geometric position of the rods when tensioned by hydraulic jack.

The DP-69-315 hydraulic jack was used as tensioning equipment, designed to draw bundles by pulling 24 high-strength steel wires Ø 5 mm.
The hydraulic jack was subjected to insignificant structural refinement, namely, the wedge liners were prevented from falling out of the gripping grooves, according to [5].

Beam casting. The concrete composition was calculated for class B 45 with fine aggregate (quartz sand) and large aggregate (crushed stone).

The mix was prepared using a SB-133 cyclical turbulent mobile concrete mixing machine brand, the loading volume of 100 l.

The weight composition of the concrete mixture: crushed stone fraction 20-100 mm - 64 kg; sand - 28 kg; M-50C cement - 27 kg; water - 14 kg. Water-cement ratio, w / c = 0.6. Concrete matures in an air-moist environment with humidity of 100% without heat treatment for 12 days.

When testing standard samples for compression at the age of 12 days, the strength $R_{\text{comp}} = 33.5$ MPa was obtained. Compaction of the concrete mixture was carried out by pervibrator.

Based on the theoretically predicted length of the anchoring zone, taking into account the FRP resistance in gripping anchor components during transverse compression, the liner length was 170 mm.

3. The results of experimental sampling analysis
The goal of the study is to assess the connection type of the FRP rods and concrete based on the data of measuring the retraction depth of FRP rods relative to the prototypes’ ends.

The reason for the retraction is the released prestressing force after the cutting in steel cross section.

The beam was divided into 4 sections during the study, Figures 3, 4.

![Figure 3. Fiberglass concrete beam model.](image)

![Figure 4. Sections of cut fiberglass concrete beams.](image)
The sequence of the beam cutting was from the middle to the ends. Thus, the first cut was made in the middle of the beam, and then the resulting halves were divided into two more sections. According to Fig. 6.17, the numbering of sections was made from left to right.

As a result of cutting the beam into 4 sections, the ends of the fiberglass rods traversed along the concrete surface of the beam.

It was decided to measure the retraction depth using the GOST 166-89 caliper.

It was assumed that such a technology would make it possible to obtain the retraction depth at each end of the beam sections along all the FRP rods, however, the final number of measurements, the results of which were accepted for processing, was 19.

The average retraction depths of fiberglass rods were:
- 2.265 mm at the ends of the beam;
- 0.5 mm in the middle sections.

The next step was to create concrete-steel connection model using LIRA-SAPR software.

4. Creation and analysis of a concrete-steel connection model using LIRA-SAPR software.

The use of one-way connections for modeling various processes of friction and tribological characteristics make it possible to recreate numerous interactions in a numerical program form, the specificity of which gives construction and technical engineers a great advantage. In particular, an objective assessment of real physical processes at the design stage simplifies and even saves the cost of work, and most importantly gives the necessary strength characteristics’ capacity.

To describe the “reinforcement-concrete” model, it is necessary to characterize the interaction of three media: reinforcement, concrete and the contact layer between.

The model was generated in LIRA-SAPR software. Spatial-volumetric finite elements with six and eight nodes were used for reinforcement and concrete. The environment of the contact layer is represented by two-node elements of one-way connection:

FE 255 - Two-node FE of elastic bonds, allow for breaking stress (analog of FE 55, allow for breaking stress).

The stiffness parameters of the main finite element were varied in its numerical description. In particular, the determination of linear stiffness R for the finite elements of unilateral connections was carried out taking into account the elastic coefficient of concrete extension. Linear stiffness R is defined as:

By default, the link element is given the value of linear stiffness, which is defined as:

\[ R = E \cdot A \cdot (1/l) \]  \hspace{1cm} (1)

where E is the elastic coefficient of the contact layer material, A is the reinforcing steel area oriented relative to the current local axis, 1 / l is the linear length within which this stiffness is valid.

![Figure 5. Assignment of stiffness parameters to one-way connection elements.](image-url)
Figure 6. Laws of the shear stress distribution according to the classification of Professor Kholmyansky [6]

The elastic coefficient of the contact layer for a first approximation is taken according to [7]. The limiting values of the compressive and tensile forces are taken taking into account the corresponding ultimate resistance according to [8].

Since the normal law of shear stress distribution along the length of the contact zone (Figure 6) is an inhomogeneous curve combining different orders, the solution is a simplified elasto-plastic approximation of the real function. 4 variants of numerical testing were performed with excellent characteristics during the simulation. The following are screenshots of the isofields of shear stresses in the steel-concrete connection area, as well as displacements in the nodes of the elements.

Figure 7. Nodal displacements, mm, at R = 2 t / m for the left beam end

Figure 8. Nodal displacements, mm, at R = 2 t / m for the right beam end
Figure 9. The pattern of the distribution of the stress isofields kN / cm\(^2\) in the steel-concrete contact area for the left beam end at R = 2 t / m.

Figure 10. The pattern of the distribution of the stress isofields kN / cm\(^2\) in the steel-concrete contact area for the right beam end at R = 2 t / m.

Table 1 presents the correlation of the displacement of the reinforcing beam end from reduction in linear stiffness.

| R, t / m | u of the end, mm | left | right | middle |
|---------|------------------|------|-------|--------|
| 5       | 0,417            | 0,403| 0,41  |
| 4       | 0,459            | 0,43 | 0,4445|
| 3       | 0,526            | 0,47 | 0,498 |
| 2       | 0,64             | 0,526| 0,583 |

Table 2 presents the dependence of the maximum shear stresses in the contact layer on the linear stiffness.
Table 2. The dependence of the maximum shear stresses in the contact layer on the linear stiffness of FE connectivity.

| R, t / m | l - t, m redistribution | \( t_{max} \) in contact layer, kN / cm² | \( t_{max} \) in reinforcement, kN / cm² |
|---------|------------------------|------------------------------------------|----------------------------------------|
|         | left | right                  | left | right                  |
| 5       | 0,487 | 0,533 | 1,63 | 8,32                  |
| 4       | 0,566 | 0,509 | 1,82 | 9,36                  |
| 3       | 0,628 | 0,569 | 2,1  | 10,9                  |
| 2       | 0,723 | 0,628 | 2,51 | 13,2                  |

5. Conclusion

As can be seen from the above, finite-element displacement in the middle sections practically coincide with the data of the full-scale experiment, however, the displacements (and the stressing respectively) in the end sections require additional research. It is planned to produce additional beams, prestressed with the low-modulus composite steel to determine the retraction depth during reinforcement tension release. Along with this, a mathematical model of the steel-concrete connection will be simulated and analyzed.

Reference

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