On the results of experimental and numerical studies of the stress-strain state of concrete structures reinforced with pre-stressed polymer composite links

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Abstract. As part of the work, experimental and numerical studies were carried out to assess the stress-strain state of concrete structures reinforced with polymer composite reinforcement. The experiment and numerical simulation obtained good consistency of the results. The research results showed that the pre-tension of links made of polymer composite reduces the deformability of the beams, by reducing the deflections by more than 4 times. Concrete structures, reinforced with pre-stressed strands of polymer composite, can be used in building structures for industrial and civil purposes, transport construction.

1. Introduction

Recently, the volume of production of polymer composite valves has increased, it has become available for construction, however, in construction practice, especially in critical structures working in tension, bending and other complex effects on structural elements, it has not become widespread. At the same time, more and more design engineers and builders are showing interest in using polymer composite reinforcement, which is determined by its positive properties, namely corrosion resistance, lack of electrical conductivity, high axial tensile strength and low specific weight, which makes it possible to use concrete structures in areas where the use of steel is structurally limited [1, 2]. The main disadvantage of polymer composite reinforcement is a low modulus of elasticity (50–60 GPa), it is closer to concrete than to steel, which leads to significant deformations and cracking of concrete structures. Slow inclusion of polymer composite reinforcement into work, and the large deformations of concrete structures associated with this, some authors have attributed to weak adhesion between concrete and polymer composite reinforcement, which undoubtedly affects the bearing capacity of the structures [3-6]. The interaction of concrete and reinforcement, as a whole, occurs due to three factors [3]: mechanical engagement of reinforcement for concrete, in the presence of irregularities on the surface of the reinforcement, friction between concrete and reinforcement, at the level of molecular interaction (cohesion). According to a number of authors, mechanical engagement of polymer composite reinforcement for concrete is currently a less reliable method, although today there are a dozen modifications of winding and surface treatment, which provide excessive adhesion indicators.
[3, 5]. However, the problem of high deformability of polymer composite reinforcement as a heterogeneous and structurally complex material persists. One of the possible ways to solve the problem is the use of pre-stressed polymer composite reinforcement of concrete structures. This method of increasing the stiffness of bending elements has been known since 1936, and is widely used to tension working links of high-strength steels. The complexity of the technological process of tension polymer-composite reinforcement - in the transfer of force from the jack to the valve without loss and slippage. The issues of tension of polymer composite reinforcement by the authors of the work were studied in detail and considered in the article [6]. This paper presents the results of numerical and experimental studies of the stress-strain state and the nature of the destruction of structures reinforced with pre-stressed polymer composite links, which is of practical interest for designers and builders.

2. Experimental studies
As part of the experiment, tests were carried out on the effect of vertical static load, leading to bending of test specimens in the form of beams and slabs.

At the first stage, concrete beams with dimensions of 0.12×0.2×1.8 m with fiberglass (FG) prestressed sand-coated reinforcement (“sandy”) were made as prototypes. The beams are made of concrete B25 and B30 with a single reinforcement: the lower zone - pre-stressed working reinforcement - Ø6 FG, the upper zone - constructive reinforcement - Ø4 FG. The tension of the link was carried out using a special installation, equipped with a jack with a dynamometer. The samples at one end rested on a pivotally fixed support, and the other end on a pivotally movable support (Fig. 1, Fig. 2a).

![Figure 1. The scheme of support and loading of the tested beams](image1)

![Figure 2. Testing experienced beams: a - loading scheme of an experienced beam; b - the nature of the destruction of the beam](image2)
The destruction of concrete beams of class $B30$ occurs at a load of 15 kN (Fig. 3a), while the deflection of the beam is equal to $f = 4\, \text{mm}$, which is equal to $1/400$ relative to the length of the beam span $l$. For beams from concrete class $B25$ (Fig. 3b), the breaking load is $12\, \text{kN}$, which is 14.7 percent less than for beams from concrete with a class higher. The deflection in the middle of the span was $2.8\, \text{mm}$, which is about $1/570$ relative to the length of the beam span. The nature of the destruction of the beams occurs predominantly along the line of action of the loads in the form of the formation of an inclined crack in the lower zone of the beam with the subsequent brittle destruction of the prestressed link (Fig. 2b). During the experiments, beams were destroyed along a normal crack in the zone of pure bending, and in these cases the ultimate load during the destruction of beams increased on average by 18 percent.

![Figure 3. Graphic dependences of average values of “load $P$ - deflection $f$ ” for beams from concrete of class a - $B30$; b - $B25$](image)

If you carry out a comparative analysis with the results of studies of the work of bent elements of concrete beams reinforced with polymer composite reinforcement by other authors [8–12], then beams without reinforcement prestressing under the influence of the load are highly deformable, the maximum deflection was $1/38 – 1/64$ of the calculated span investigated beams, crack opening at the same time reached $1.1–1.7\, \text{mm}$.

With the destruction of prototypes of beams with prestressed polymer composite reinforcement, the relative deflection did not exceed the standard value of $l/400$, but the value of crack opening exceeded $0.4\, \text{mm}$, which does not affect the corrosion resistance of the elements reinforced with polymer composite reinforcement. Comparison of bearing capacity can be made in terms of $M_{ult}$/l is the relative destructive moment, and crack resistance according to $M_{crc}$/l is the relative moment of formation of cracks, the results are listed in Table 1.

The test results show that the bearing capacity of elements directly depends on the number and diameter of polymer-composite reinforcement, the value $M_{ult}$/l = 2.57 for prestressed beams, for beams without tension 5.529, the value is twice as much due to the fact that two links were used in the stretched zone Ø6. The relative moment of formation of cracks $M_{crc}$/l for beams with tension polymer-composite reinforcement is 2.133, and without tension 0.645–1.94, that is, an increase in the number of links twice, does not reduce the deformations of the tested beams, and does not increase the relative moment of cracking.
Table 1. Comparison of bearing capacity can be made in terms of \( M_{\text{ult}} / l \) is the relative destructive moment, and crack resistance according to \( M_{\text{crc}} / l \) is the relative moment of formation of cracks

| Object of study                  | Element Characteristics                      | Indicator   |
|---------------------------------|---------------------------------------------|-------------|
| Beams with prestressed          | Span 1600 mm, one reinforcement Ø6 (FG), concrete class B25 | \( M_{\text{crc}} / l \) | \( M_{\text{ult}} / l \) | \( f_{\text{max}} / l \) |
| reinforcement                   |                                             | 2.133       | 2.57          | 1/570         |
| Beams without prestressed       | Span 900 mm, one reinforcement Ø6 (FG), concrete class B20 [9] | 0.635       | 1.505         | 1/64          |
| reinforcement                   | Span 1700 mm, one reinforcement Ø6 (FG), concrete class B25 [8] | 1.94        | 5.529         | 1/38          |

3. Numerical investigations

A workable and adequate numerical model for the joint operation of concrete with prestressed polymer composite reinforcement (FG) based on finite elements requires comparison and analysis with empirical data obtained as a result of the experiment. The convergence of the numerical model will help evaluate and derive some of the design characteristics, as well as provide an opportunity to form more complex models with pre-stressed reinforcement for use in various designs. There are many models of adhesion of concrete and reinforcement [3] and the formation of a grid of finite elements, methods of creating preliminary efforts in the core elements, forms describing the nonlinearity of materials, all this can be used to mathematical description of the model of a pre-stressed beam.

Some authors works can be noted in which, on the basis of finite-element models, the processes of deformation of reinforced concrete structures are implemented in the framework of linear [18] and non-linear models [20, 21] of reinforcement, including in the framework of contact interaction of structural elements with each other and with the surrounding their soil [19−23].

There are limitations that exist when using numerical simulation software packages: ANSYS, Nastran, ABAQUS, Midas, LIRA-SAPR and others that affect the calculation results, therefore two models were formed in the LIRA-SAPR 2016 and ANSYS 14.0 programs [13]. The initial characteristics of the model are the geometrical parameters of the prototypes, the physical characteristics of the materials are described by piecewise linear dependencies.

![Figure 4](image)

**Figure 4.** Dependences of stresses on deformations: a - for concrete, b - for polymer composite reinforcement

The graph of dependence is based on points with coordinates for concrete (Fig. 4a): \( \sigma_{b1} = 0.6R_y = 10.2 \text{ MPa} \), \( \epsilon_{b1} = 0.000313 \); \( \sigma_{b2} = R_y = 17 \text{ MPa} \), \( \epsilon_{b2} = 0.002, \epsilon_{b1} = 0.0035 \); for
reinforcement (Fig. 4b): \( R_f = 1000 \text{ MPa} \), \( \varepsilon_{f0} = 0.02 \), with \( \varepsilon_{f0} \leq \varepsilon_f \leq \varepsilon_{f2} \), the dependence is ignored. The initial tension of the reinforcement bar is taken in the amount of \( \sigma_p = 500 \text{ MPa} \).

In the LIRA – SAPR 2016 program, the spatial finite element model of the beam is created from bulk and core (truss) finite elements (hereinafter referred to as FE). Concrete was modeled by volumetric elements, and reinforcement was used for pivot elements. The calculation was made taking into account the physical non-linearity of concrete by the step method.

The simulation results obtained significant discrepancies with the experiment. As can be seen from Figure 5, volumetric finite elements of concrete are not disconnected from work when achieving the design characteristics, which impedes the evaluation of the full-fledged operation of core elements.

![Figure 5. Isopole of normal stresses in concrete in the software package LIRA-SAPR 2016](image)

The creation of the FE model in the ANSYS 14.0 program [13] was carried out in the same way: the preliminary tension in the lower link was set by its fictitious cooling, which implements a tensile stress of 500 MPa. It was assumed that in concrete the axial tensile stress of crack formation under a uniaxial stress state was 3 MPa, and the transmission coefficient of tangential stress for a crack was 0.45.

It can be noted that in the calculation of reinforced structures taking into account the crack formation in concrete, the ANSYS 14.0 program has already been used more than once, and in some works some recommendations were made on its use [16, 17]. However, as shown by numerical experiments, the use of the calculation parameters proposed in [16] at the ANSYS 14.0 program, and especially the recommended value of the “Tol” residual parameter, gives good results when describing the deformation of a reinforced structure at a sufficiently long loading stage if it is not used prestressed steel bars reinforcement. When using composite reinforcement, the experiment shows that its destruction after the occurrence of the main crack occurs almost instantly. Therefore, when using the calculation scheme used in the work, the standard convergence parameters of the ANSYS 14.0 program were used.

The calculation was made by the step method, and the “tension” of the lower link is modeled at the “zero” step. Further loading is modeled with a transverse load step of 1 kN. Based on the symmetry of the problem, only one fourth of the beam was simulated: symmetry was considered over the central cross section and along the longitudinal vertical section. In this case, it was possible to observe the stress state in the area where the reinforcement bars are located.

The simulation results show the following stress-strain state of the beam. The process of cracking in the beam is shown below:
• in Figure 6a - the stage of “zero” loading step, where the lower bar tension occurs;
• in Figure 6b - for the 14th loading step, the achieved load is 14 KN;
• in Figure 6c - for the 18th loading step, the achieved lateral load of 18 KN.

It should be noted that the result of a numerical study of the pre-stressing of the lower link causes a process of crack formation at the ends of the beam. Upon further loading with a vertical load to the level of 14 KN, the first cracks appear in the lower zone of the middle part of the beam span, and at a load of 18 KN the cracks propagate along the entire height of the beam and almost all efforts are redistributed to the reinforcement, which collapses when the load reaches 28 KN.

Note that the pattern of crack formation is very similar to that obtained when testing beams, however, the actual breaking load is about 12 KN, so it is possible to adjust the design scheme, which will reduce the level of breaking load. First, the effective stresses in the pre-stressed link are less than the calculated ones, which is caused by some relaxation of the stresses in the operating beam. Secondly, in the area of the end of the beam, reinforcement may be slipping relative to concrete. Thirdly, the destruction of a pre-stressed link can occur at a lower load, and not at 1000 MPa. Varying these three parameters in the course of a computational experiment, we can get the dependence of the maximum deflection in the mid-span of the beam on the magnitude of the applied load is the same as in Figure 3b. At the initial pre-stress of the composite link, $\sigma_{wp} = 338 \, MPa$, the length of the section of the lower pre-stressed link (from the beam end), through which separation from the concrete occurs $L_f = 39.5 \, cm$, the stress at which the lower link breaks $R_f = 694 \, MPa$. The dependence of the deflection in the center of the beam on the loading steps for this version of the calculation is shown in Figure 7.
When increasing the class of concrete to B30, the combination of graphs of numerical and experimental studies occurs at initial pre-stress $\sigma_{wp} = 325 \text{ MPa}$, the length of the section of the lower pre-stressed link (from the beam end), in which the separation from the concrete occurs $L_f = 37.9 \text{ cm}$, the stress at which the lower link breaks $R_f = 676 \text{ MPa}$.

![Graph of load vs. deflection](image)

**Figure 7.** Graphic dependences of “load $P$ - deflection $f$ ” in the numerical simulation in ANSYS 14.0 program

### 4. Conclusion

Tension, as the process of pre-deformation of reinforcement, does not increase the bearing capacity of the beams, but reduces the deformation of structures, providing standard deflections and increasing their crack resistance.

According to the test results, it was revealed that the preliminary tension of the links made of polymer composite reduces the deflections by more than 4 times. Concrete structures reinforced with pre-stressed cores of polymer composite can be used in building structures for the construction of industrial, civil and transport objects.

According to the results of a comparison of experimental and numerical studies, the numerical model of a pre-stressed beam created in the ANSYS 14.0 program correctly describes the test results, the deviations are no more than 5 percent.

Numerical studies show that as a result of losses in the manufacture of beams, the initial tension of the link decreases by about 35 percent, deformations at the ends of the beams lead to slippage of the links, as well as to a decrease in the compression force of concrete in the lower zone of the beam. The axial tensile strength of the bar is used by 69 percent.

Analysis of the numerical results obtained on the basis of the ANSYS 14.0 program within the framework of the proposed calculation scheme shows that using this approach to describe the deformation of the pre-stressed reinforced concrete structure is acceptable for the technical calculation, and the results are confirmed by experimental data. However, for a more accurate description of the deformation process, it is necessary to somewhat complicate the implemented model. In particular, since in the process of deforming the reinforced structure, especially when it is bent, partial slippage of reinforcement beams inside the concrete inevitably occurs, it is necessary to
take into account the contact interaction between the reinforcement and the concrete, and to determine the strength of the bond breaking between them from a numerical experiment, comparing the results obtained with experimental data. The possibility of constructing such a refined model of the deformation of reinforced structures in the ANSYS 14.0 program is available.

Technical solutions for the implementation of concrete structures reinforced with pre-stressed polymer composite links in construction have corrosion resistance, lack of electrical conductivity, high axial tensile strength, reduced construction weight and can be used in building structures with appropriate justification and calculations.

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