Modeling of the Stress-Strain State of a Composite External Strengthening of Reinforced Concrete Bending Elements

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Abstract: The paper deals with the issues and features of modeling of external reinforcement of reinforced concrete structures with bending using ANSYS software. The technique of modeling of the bent reinforced concrete elements strengthened in the stretched zone by external reinforcement from composite materials approved by full-scale experiments is given. This clarification of the application of the methodology with different approaches to the strengthening of the structure. The qualitative and quantitative dependences between experimental and numerical studies confirming the prerequisites of the study are established.

1. Introduction

One of the most dynamically developing ways to strengthen reinforced concrete structures in the European and domestic construction market is the method of external reinforcement with high-strength non-metallic materials. The maximum efficiency of the method is achieved by the use of high-modulus materials in the areas receiving the greatest tensile forces. However, to calculate the required parameters of the gain elements, such as the calculated resistance, cross-sectional area, anchorage length, etc. at the stage of operation of a reinforced structure under load, a flexible mathematical apparatus is required that can take into account the transformation of the design scheme into a statically indeterminate one, the differences in the deformation characteristics of materials and the compatibility criteria of the deformations of the reinforced structure and the reinforcement elements.

Currently, experimental and numerical studies of reinforced concrete elements reinforced with external composite reinforcement have been carried out, the results of which have been published. In [1] the modeling of a two-span hinged beam, including reinforced with composite clamps in the area of the middle support, is considered. Amplification was performed to increase the bearing capacity of the inclined section. The simulation was performed in the ANSYS 18 software package. The concrete was modeled by finite elements of SOLID65 type, longitudinal and transverse working steel reinforcement - rod finite elements LINK180. The external reinforcement was modeled by a shell finite element of type SHELL181, and the connection between it and the concrete surface was defined by means of the finite elements CONTA173 and TARGET170. A two-line diagram was adopted as a General form of the deformation law. The computer experiment allowed us to obtain a forming zone and path disclosure of critical inclined crack, the magnitude of the extrema principal stresses in the
stretched area, the stress values in the clamps the gain. In the course of comparing the results obtained in the program and the results obtained in the calculation according to the normative documents [2-4], it was found that the application of the author's modeling technique allows to increase the calculated bearing capacity for the perception of the transverse force of non-reinforced beams by 6-10% compared to [2] and by 12% compared to [3, 4] in the case of amplification. The critical stresses in the external reinforcement obtained by the author are 73-167% higher than those obtained in the calculation of [1, 2] and approach the experimental values.

In [5-6] the modeling of the normal cross sections of bridge beams amplification by carbon composites in the stretched zone is considered. The modeling technique in the ANSYS 18 complex is used, which is practically similar to that described in [1], except for the method of specifying the interaction between concrete and composite: instead of contact and target FE surfaces, a conditional adhesive layer consisting of SOLID65 elements with passport parameters is used. The calculation according to this method showed a decrease in the calculated bearing capacity for the action of the bending moment in comparison with the experiment by 2-14%.

Thus, a comparative analysis of the results of experimental and numerical studies conducted by different authors showed that there are several applicable approaches to the modeling of reinforced concrete elements with external reinforcement as composite beams. The greatest interest is the question of setting in the program the nature of the interaction of heterogeneous layers of the structure [7-9].

2. Methods
The aim of the numerical studies was to carry out computer simulation of the work of reinforced concrete structures under load, with and without external reinforcement. The simulation was carried out to determine the parameters of strength and deformability of bent structures with several different approaches to the method of specifying the nature of the interaction between the amplified element and the amplification element.

To conduct a comparative analysis before the numerical experiment, full-scale tests of 4 series of reinforced concrete beams were carried out in accordance with the author's technique described in [10-12]. During the experiment, the values of the bearing capacity of the bending moment, the deflection and the width of the opening of the critical crack in the zone of pure bending were fixed.

The FEM-complex ANSYS 18 was used as a platform for the numerical experiment. It allows you to model and calculate the design of any configurations and designs, perform the selection of sections and carry out the necessary checks.

The beam model was composed of three-dimensional finite elements with specified strength and deformation parameters of materials (see Fig. 1), boundary conditions and external load given as a function of time.

The implicit differential equation solver is used in the calculation. The solution of the nonlinear problem by the iterative tangent method with automatic step optimization (provided that the iterations are exceeded). The iterative solver in ANSYS 18 is implemented by the conditioned conjugate gradient method. Control of load convergence was set in the range of 2-5%.

Concrete was modeled by finite elements of SOLID65 type. The concrete work is described by the William-Warnke model (Geniev's strength criterion). Two mechanisms of failure are considered: from the loss of compressive strength and from the loss of tensile strength. The classical five-line state diagram is accepted as a deformation model. The falling branch of the diagram simulates the reduction of the elastic modulus after the concrete reaches the stress limit. Longitudinal and transverse working steel reinforcement was described by rod end elements of LINK180 type. A two-line Prandtl diagram was used as a deformation model. The composite reinforcement material was modeled by shell finite elements of the SHELL181 type. The external load was applied to the beam through the distribution plates - the final elements of the SOLID65 type.
The size of the final elements is differentiated: for concrete - 20mm, for steel reinforcement - 4mm, for distribution plates and external reinforcement - 10mm.

For a more complete analysis of the model, 3 variants of interaction of shell elements of the composite with the concrete surface were applied:

1. Rigid coupling (Bonded);
2. Finite element modeling of the CONTA173 and TARGE170 types. The diagram obtained in the course of statistical processing of the test results described in [10, 13-14] is accepted as a deformation model.
3. Friction connection with variable coefficient of friction (Frictional). The range 0.8-1.0 was chosen for the experiment.

It should be noted that the method of modeling the contact zone in the form of bulk solid elements with the specified parameters determined during experimental studies [11] simulating the adhesive compound [15] gave high errors (more than 50%) in comparison with the experimental data. The results obtained by this method were not included in the analysis.

Together with the analysis of the applicability of a particular method of creating a model of reinforced concrete element with external reinforcement, the authors also had the task to develop a method for specifying the initial data on the presence of stresses and strains in the reinforced element at the amplification stage. After a series of 3-4 meant increased after exposure to the element some of the load. The problem was solved by programming in APDL environment and operator SVAR. For series 3, preloading was set by recording plastic deformations and state variables in the preliminary calculation of the non-violent element (with the composite element disabled) into a temporary file:

```
inistate,set,csys,-1
inistate,set,dpyp,eppl
inistate,set,dpyp,svar
inistate,def,all,all,all,eppl,..
inistate,set,mat,3,4,5,10
inistate,write,1,,,,,fileB-3-1,ist
inistate,read,fileB-3-1,ist / inistate,read,fileB-3-2,ist
solve
```

After activation of the composite element, the mesh nodes were moved to the deformed position, the information about the state of the material was read from the file, the load was applied again:

```
upgeom,,,,,fileB-3-1,rst / upgeom,,,,,fileB-3-2,rst
inistate,read,fileB-3-1,ist / inistate,read,fileB-3-2,ist
```
solve

The calculation for the series 4 was produced similarly, except for the additional recording of elastic deformation:

\[ \text{inistate, set, csys, -1} \]
\[ \text{inistate, set, dtyp, epel} \]
\[ \text{inistate, set, dtyp, stre} \]
\[ \text{inistate, defi, all, all, all, all, s, epel, .} \]
\[ \text{inistate, set, mat, 3, 4, 5, 10} \]
\[ \text{inistate, write, 1, . . . , -1, epel} \]
\[ \text{inistate, write, 1, . . . , -1, s} \]

solve

3. Results and discussion

As a result of the numerical experiment, the isofields of the main stresses, strains and displacements were obtained. As an example, figure 2 shows the deformation isofield of the sample B-3-2.

![Figure 2. Isofield of relative (top) and equivalent (bottom) deformations B-3-2.](image)

The data obtained from the program for different approaches to the task of compatibility of concrete and composite material were compared with the results of full-scale tests of samples. The difference between theoretical and experimental data is presented in table 1.

The results of numerical studies show high convergence with the results of the full-scale experiment. The most accurate data were obtained by modeling the contact zone "composite-concrete" with the help of finite elements of the target surfaces with the task of the law of interaction, developed in [11-12, 14]: the magnitude of the deviation of the bending moment strength was 0.5% for the b-2 series, 4.47% for the B-3 series, 2.91% for the B-4 series. The stiffness deviation was 2.2% for the B-2
series, 6.35% for the B-3 series and 18.18% for the B-4 series. The crack opening width at all stages of

The crack opening width at all stages of crack formation did not exceed the experimentally obtained one.

**Table 1.** Changes in the results of the numerical study using different calculation methods compared with the experimental results.

| Marking of the sample | Design methodology          | Ultimate bending moment | Vertical deflection in the middle of the span | Normal crack opening width |
|-----------------------|-----------------------------|-------------------------|---------------------------------------------|---------------------------|
|                       | rigid                       | multiline clutch        | friction connection                         |                           |
| B-2-1                 | +19.76%                     | 0%                      | -1.8%                                       | -3.08%                    |
| B-2-2                 | +3.18%                      | -1%                     | -2.67%                                      | +1.5%                     |
| B-3-1                 | +17.5%                      | +1.05%                  | +5.35%                                      | +4.6%                     |
| B-3-2                 | +21.58%                     | +7.9%                   | +12.3%                                      | +14.34%                   |
| B-4-1                 | +19.56%                     | +1.19%                  | -5.06%                                      | +2.2%                     |
| B-4-2                 | +21.76%                     | +4.63%                  | -7.7%                                       | +1.53%                    |

«+» means an increase in the index compared to the experiment

«-» means a decrease in the index compared to the experiment

The results closest to the experimental ones are highlighted in bold.

The application of the technique hard the clutch gives higher values of strength and stiffness of elements [14]: the amount of deviation of strength for the bending moment action amounted to 11.47% for the series B-2, 19.54% for the series B-3, and 20.66% for the series B-4. The stiffness deviation was 27.87% for the B-2 series, 21.46% for the B-3 series and 18.18% for the B-4 series. The crack opening width at all stages of crack formation did not exceed the experimentally obtained one.

The application of the technique is pliable friction joints underestimate the experimentally obtained data: deviation of strength to the action of bending moment amounted to 11.85% for the series B-2, 3.8% for the series B-3 and 5.99% for the series B-4 and hard – 11.27% for the series B-2, 13.32% for the series B-3 and 1.86% for the series B-4. The crack opening width at all stages of crack formation is larger than the experimentally obtained one.

The results of series 2 have a high convergence with the results of the authors’ studies [5, 6, 17, 18] on the part of the limiting bending moment and the width of the normal crack opening. Comparison on parameters of rigidity of beams was not carried out due to lack of these data at the listed authors. The authors of this article associate this with the unity of methodological approaches to the description of the joint work of concrete and external reinforcement, despite the different ways of its job.

In addition, during the numerical study by the method of a multi-line diagram, graphical images of the post – stage fracture of the contact zone "composite-concrete" were obtained, which is shown in
figure 3. It shows the distribution of the relative deformations of the side and bottom faces of the beam during the application of the load in the range of 25-100% of the breaking in increments of 15%. The figure clearly shows the accumulation of deformations in the area of the joint of the external reinforcement with the anchor, the movement of the point of maximum deformations (red flag) from the span of the beam to the support, as well as the zone of the beginning of peeling of the composite element. The analysis of color indication of deformations allows us to conclude that the "pliable" model shows a picture more similar to reality, which is indirectly confirmed by the conclusions [19-21]. The nature of the destruction and the zone of exfoliation from the concrete in the software complex coincide with those obtained during full-scale tests. Linking the model to a scale bar can determine the effective anchorage length, as well as the most vulnerable points that require additional anchors.

![Figure 3](image)

**Figure 3.** Characteristic deformation processes of external reinforcement peeling in the case of "rigid" model (left) and "pliable" model (right).

4. **Conclusions**
   - The numerical experiment shows that the external reinforcement brings a positive effect to the work of reinforced concrete bending elements and increases their bearing capacity and stiffness, as well as reduces cracking in the pre-limit stages.
The performed comparative analysis showed that one of the decisive factors in the calculation of composite structures is the method of modeling the joint operation of adjacent layers of the structure with different deformation characteristics [11-13, 31].

In general, the most complete and accurately reflecting the actual work of the contact zone method is the task in the form of a diagram of the law of deformation obtained on the basis of statistical processing of the results of experimental studies.

An important task in the design and modeling is the accumulation of a sufficient base of the results of practical tests of work under the load of the contact zone "composite-concrete" for different classes of concrete reinforced structure and mechanical parameters of reinforcement materials, as the data given by the authors are valid only for specific classes of concrete and reinforcement.

The use of volumetric elements for modeling thin shell structures that are part of a multilayer structure is irrational and leads to high distortion.

First obtained by the graphical display of the deformation elements of the external reinforcement at the approach to the exorbitant states are strengthening beams that most closely mirrors the real picture obtained in the field experiment.

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