

Modeling of stress-strain state of external reinforcement of single-span reinforced concrete beams

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Abstract. The paper touches upon the issues and features of computer modeling of external reinforcement of reinforced concrete beams with the use of computer complex ANSYS. The method of modeling of bent reinforced concrete beams reinforced in the stretched zone by external reinforcement based on carbon fiber composite materials, approved by experimental studies, is presented. The explanations on application of a technique at various approaches to strengthening of a beam depending on the current stress-strain state are given. Qualitative and quantitative dependences between experimental and numerical studies are established, confirming the initial prerequisites of the study.

1. Introduction

One of the most dynamically developing ways to strengthen reinforced concrete elements and structures in the world construction market is the method of external reinforcement with high-strength non-metallic materials. Maximum efficiency is achieved when using high-modulus materials in areas that receive the greatest tensile forces. Such materials are, among others, composites based on carbon fibers. However, for the calculation of these design parameters elements of the gain, as the design resistance in tension, the cross-sectional area, length, embedment, etc., as well as checking calculations at the stage of operation under load requires a flexible and well-adapted mathematical tools able to take into account the transformation of the design scheme construction during the work under load, the differences in the deformation characteristics of materials and criteria of teamwork strengthen structures and reinforcements.

Nowadays the experimental and numerical studies of the work of reinforced concrete elements reinforced with external composite reinforcement have been carried out, the results of which have been processed and published. In the work [1] the modeling of a two-span articulated beam, including reinforced with composite clamps in the area of the Central support, is considered. The reinforcement was carried out to increase the bearing capacity of the inclined section. The numerical experiment was performed in the ANSYS 18 software package. Concrete was modeled by SOLID65 end elements, longitudinal and transverse working steel reinforcement by LINK180 rod end elements. The external reinforcement was modeled by a shell finite element of type SHELL181, and the connection between it and the concrete surface was specified by finite elements CONTA173 and TARGE170. A two-line diagram was adopted as a General form of the deformation law. The computer experiment made it possible to obtain zones of formation and trajectories of critical inclined cracks, values of extremes of



the main normal stresses in the stretched zone, values of stresses in the reinforcement clamps. During the comparison of the results obtained in the program and results calculated according to approved normative documents, it was found that the use of the author's technique of modeling allows increasing the estimated carrying capacity for the perception of transverse forces not strengthened beams 6-10%] and 12% in the case of gain. The critical normal stresses in the external reinforcement obtained by the author are 73-167% higher than those obtained in the calculation according to the norms and approach the experimental values.

In [2] modeling of strengthening of normal cross-sections of bridge beams by carbon composites in the stretched zone is considered. The method of modeling in the ANSYS 18 complex is used, similar to the one described in [1], except for the method of specifying the interaction between concrete and composite: instead of contact and target contact surfaces, a conditional adhesive layer consisting of SOLID65 elements with passport parameters is used. The calculation by 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%.

A comparative analysis of the results of experimental and numerical studies conducted by different authors taking into account the work on different schemes in General showed that there are several applicable approaches to modeling reinforced concrete elements with external reinforcement as multilayer elements. The greatest interest in this case is the question of setting in the program the nature of the interaction of adjacent heterogeneous layers of the structure [3, 4].

The purpose of the numerical studies was the implementation of computer simulation of bending reinforced concrete beams under load, with external reinforcement and without it. Modeling was carried out to determine the parameters of strength and deformability of the bent elements with several different approaches to the method of specifying the nature of the interaction of the reinforced element and the reinforcement element.

2. Methods

In order to conduct a comparative analysis before the numerical experiment was carried out full-scale tests of 4 series of reinforced concrete beams in accordance with the author's methodology set out in [5, 6]. During the experiment, the values of the bending moment bearing capacity, deflection and width of the critical crack opening in the zone of pure bending were recorded.

The FEM complex ANSYS 18 was used as a platform for the numerical experiment. The beam model was created from finite elements with specified strength and deformation parameters of materials (see Figure 1), boundary conditions and a linearly varying external load given as a function of time.

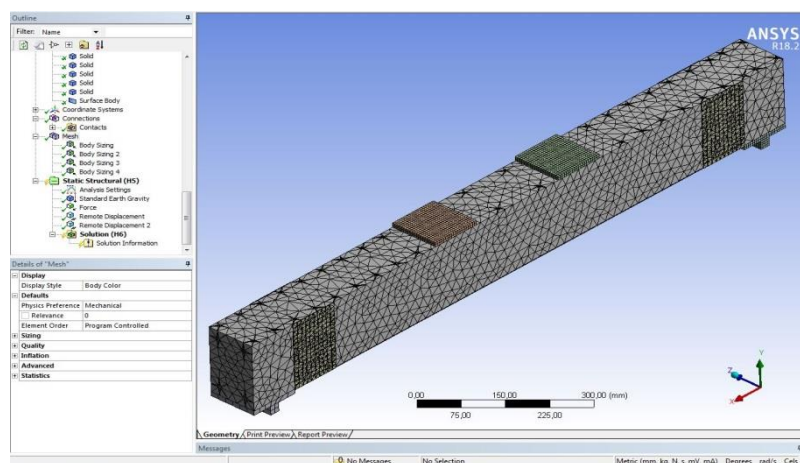


Figure 1. General view of the finite element beam model

An implicit differential equation solver is used in the calculation, and the solution of the nonlinear problem is performed by the iterative tangent method with automatic step optimization (provided that iterations are exceeded). The iterative solver in ANSYS 18 is implemented by the method of conditioned conjugate gradients. The load convergence control was set to 2%.

The concrete was modeled by finite elements of type SOLID65 with a size of 20mm. The concrete work is described by the William - Warnke model (according to the Geniev strength criterion). Two mechanisms of fracture from loss of strength are considered: compression and tensile. As a deformation model, a classical five-line state diagram with a descending branch of the diagram modeling the decrease in the modulus of elasticity when the concrete reaches the limit stress level is adopted. Longitudinal and transverse working steel reinforcement was described by rod end elements of type LINK180 of 4mm size. A two-line diagram of Prandtl was used as a deformation model. The composite reinforcement material was modeled by shell finite elements of the SHELL181 type with a size of 10mm. the External load was applied to the beam through distribution plates-finite elements of the SOLID65 type.

For a more complete analysis 3 variants of interaction of composite shell elements with concrete were used in the model:

1. Rigid coupling (Bonded);
2. Modeling by finite elements of type CONTA173 and TARGE170. The diagram obtained during statistical processing of test results stated in [6] 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 solid volume elements with specified strength and deformability characteristics determined in the course of experimental studies simulating an adhesive joint [7] gave errors of more than 50% compared to experimental data, so the results obtained by this method were not included in the analysis.

Together with the analysis of the applicability of methods for creating a model of a 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 reinforcement stage. After all, series 3 and 4 meant strengthening after exposure to a certain level of operational load on the element. The problem was solved with the help of programming in the APDL environment and the SVAR operator. For series 3 preloading was defined by recording plastic deformations and state variables in the preliminary calculation of an unstressed element with the composite element disabled to a temporary file by entering commands:

```
inistate, set, csys, -1
inistate, set, dtyp, eppl
inistate, set, dtyp, svar
inistate, defi, all, all, all, all, eppl,,
inistate, set, mat, 3, 4, 5, 10
inistate, write, 1,,, -1, eppl
inistate, write, 1,,, -1, svar
solve
```

After the activation of the composite element, the grid nodes were moved to the deformed position, 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 series 4 was made similarly, except for the introduction of an additional record of elastic deformations:

```
inistate, set, csys, -1
inistate, set, dtyp, epel
inistate, set, dtyp, stre
```

```

inistate, defi, all, all, all, all, s, epel,,
inistate, set, mat, 3, 4, 5, 10
inistate, write, 1,,, -1,epel
inistate, write, 1,,, -1, s
solve

```

3. Results and Discussion

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

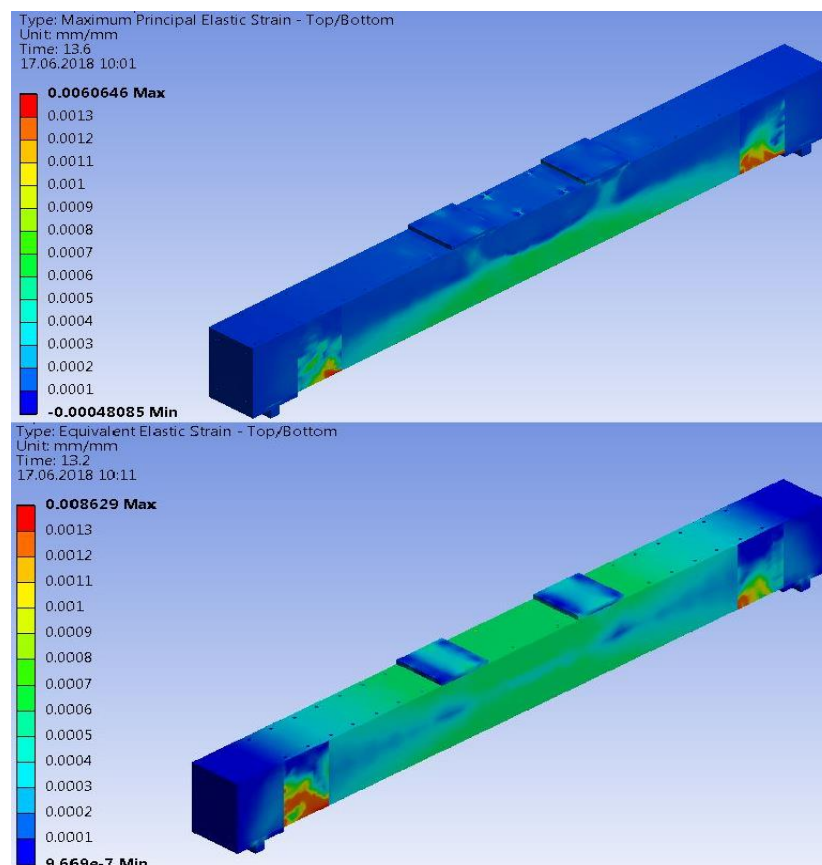


Figure 2. Isofield of relative (top) and equivalent (bottom) deformations B-3-2

The data obtained from the program for different variants of the approach to the task of compatibility of concrete and composite material were compared to 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 full-scale experiment. The most accurate data were obtained when modeling the contact zone "composite-concrete" using finite elements of target surfaces with the law of interaction developed in [6]: the value 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 value of the crack opening width at all stages of crack formation slightly exceeded the experimentally obtained one.

The application of the rigid coupling technique gives inflated values of strength and bending stiffness of the elements: the value of the deviation of the bending moment strength was 11.47% for the B-2 series, 19.54% for the B-3 series, 20.66% for the B-4 series. The bending 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 value of the crack opening width at all stages of crack formation is less than that obtained experimentally.

Table 1. Changes in the results of the numerical study using different computational methods in comparison with the experimentally obtained results

Marking of the sample	Calculating methodology		
	Rigid	Multilinear diagram	Friction connection
Maximum bending moment			
B-2-1	+19.76%	0%	-6.2%
B-2-2	+3.18%	-1%	-16.3%
B-3-1	+17.5%	+1.05%	-6.6%
B-3-2	+21.58%	+7.9%	-1%
B-4-1	+19.56%	+1.19%	-7.12%
B-4-2	+21.76%	+4.63%	-4.86%
Vertical deflection in the middle of the span			
B-2-1	-30.75%	-1.8%	-1.8%
B-2-2	-25%	-2.67%	-4.4%
B-3-1	-26.58%	+5.35%	+12.3%
B-3-2	-16.34%	+5.34%	+14.34%
B-4-1	-18.35%	-5.06%	+2.2%
B-4-2	-18%	-7.7%	+1.53%
Opening width of normal crack			
B-2-1	-24.93%	-3.08%	+1.8%
B-2-2	-16.32%	+1.5%	+5.3%
B-3-1	-6.27%	+4.6%	+10%
B-3-2	-11.38%	+4.3%	+7.2%
B-4-1	-20%	-3.6%	-1.46%
B-4-2	-17.2%	+1.1%	-1.33%

"+" indicates an increase in the indicator compared to the experiment

"- " indicates a decrease in the indicator compared to the experiment

The results closest to those obtained experimentally are highlighted in bold.

The application of the method of malleable friction connection underestimates the experimental data: the deviation of the bending moment strength was 11.85% for the B-2 series, 3.8% for the b-3 series and 5.99% for the B-4 series, and the bending stiffness was 11.27% for the B-2 series, 13.32% for the B-3 series and 1.86% for the B-4 series. The width of crack opening at all stages of crack formation was greater than that obtained experimentally.

The results of series 2 have a high convergence with the results of the authors' studies [1-4, 8] in terms of the limiting bending moment and the width of the normal crack opening. The comparison of parameters of rigidity of beams was not carried out owing to absence of these data at the listed authors. The authors of this article attribute this to the unity of methodological approaches to the description of the joint work of concrete and external reinforcement, despite the different ways of its assignment.

In addition, during the numerical study by the method of multilinear diagram, graphic images of the post – stage destruction of the contact zone "composite-concrete" were obtained, which is shown in figure 3. It shows the distribution of 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 destructive step of 15%. The figure clearly shows the accumulation of deformations in the zone of the joint of the external reinforcement with the anchor, the movement of the point of maximum deformations (red flag) from the span part of

the beam to the support, as well as the zone of the beginning of peeling of the composite element. Analysis of the color indication of deformations allows concluding that the conditionally "pliable" model shows a more similar picture to the real work, which is indirectly confirmed by the conclusions [6]. The nature of the destruction and the zone of peeling from the concrete in the software complex coincide with those obtained in full-scale tests. Linking the model to the scale bar can help determine the effective anchor length, as well as the most vulnerable points that require additional anchors.

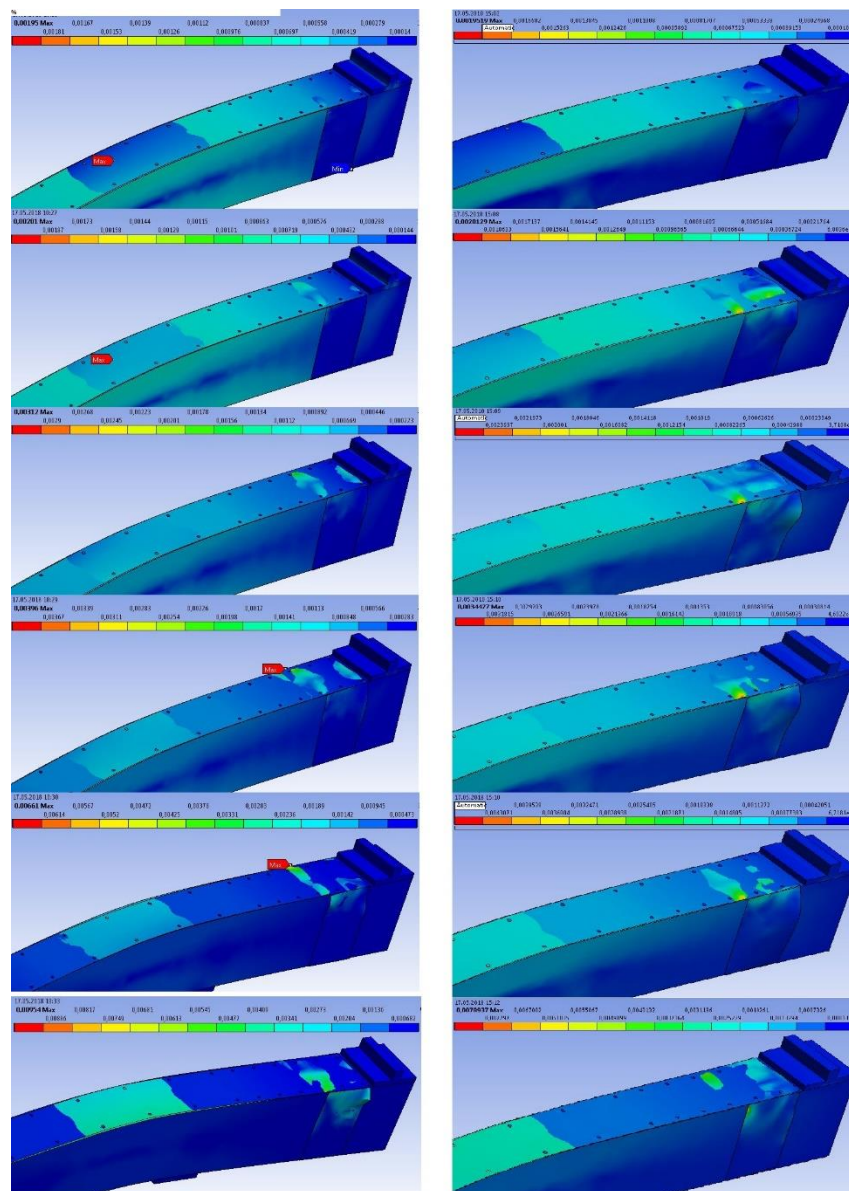


Figure 3. Characteristic isofields of deformations at processes of peeling of external reinforcement in case of use of "rigid" model (on the left) and "pliable" model (on the right)

4. Conclusion

Numerical experiment shows that external reinforcement brings a positive effect to the work of reinforced concrete beams and increases their bearing capacity in normal sections and bending stiffness, as well as reduces the normal cracking in the pre-limit stages.

The performed comparative analysis showed that one of the decisive factors in the calculation of composite multilayer structures is the method of modeling the joint work of neighboring layers with different deformation characteristics [6, 8].

In General, the most complete and accurate way to reflect the actual work of the contact zone is the task in the form of a diagram of the deformation law obtained on the basis of statistical processing of the results of experimental studies.

An important task in the design and modeling is to accumulate a sufficient base of results of practical tests of work under load contact zone "composite-concrete" at different classes of concrete reinforced structure and mechanical parameters of reinforcement materials, because the data given by the authors of this article 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.

For the first time, a graphical representation of the deformation processes of the external reinforcement elements when approaching the beyond States of the reinforced beam is obtained, which most fully reflects the situation obtained during the full-scale experiment.

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