Contact technologies in design of reinforced concrete beams with cracks

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Abstract. The article deals with the computation of the reinforced concrete beams strength by the finite element method. The features of the material behavior are considered, the reasons for obtaining erroneous results are considered. Methods for modeling structures, leading to results that strictly correspond to the theory, are proposed.

1. Introduction

Despite the high development status of the up-to-date finite elements method (FEM) and models of concrete [1] – [4], the problem of reinforced concrete structures section strength calculation using this method is still not solved. In most cases, calculation considers non-linear material properties are done to obtain elemental forces. After that, a strength test is done by way of standard calculations. The direct calculation of reinforced concrete structures under a limit state is done relatively rare and, as a rule, for research purposes. Even in these cases, the additional calibration of a simulation model to obtain results corresponding to regulatory documents is usually done.

Stresses and deformations calculation of reinforced concrete structures under a limit state with the help of the ANSYS program makes it possible to obtain the results that are in good agreement with theory in cases when the exhaustion of a structure’s bearing capacity occurs simultaneously with concrete deterioration (compressed structures [5], non-reinforced concrete bended structures). In cases when the structure is still in operation after the cracks formation (for example: bended structures with low reinforcement), serious problems of calculation may occur. This is connected to the fact, that material models in ANSYS and calculation algorithms are oriented towards materials being solid within the finite element. Any deterioration including the cracks formation during tension causes a computation to stop and serves as a structure deterioration feature. This is also related to models of concrete with cracks (Solid65 element, CONCR material). If such element is not reinforced, a crack formation also results in a computation stop. In that case, the explicit simulation of the crack fails. The problem of obtaining accurate results for reinforced concrete structures in the limiting state is quite serious and has appeared long ago. Nevertheless, research in this area is continuing [9] – [11], and the task has not been exhaustively solved to date.

After a crack formation, a strong anisotropy in material macro-volume is developed. Material stiffness along the crack remains almost constant, and significantly reduces in the direction across the crack. Difficulties during computation could be avoided if the program supported the development of
anisotropy in the deformation simultaneously process with the nonlinearity. Unfortunately, this feature is not provided in the ANSYS program (and neither in other programs). Another way is to create your own material model, using new developments in the field of plasticity of reinforced concrete [6] – [8]. But this method is too complicated for an engineer. It requires a thorough testing of the model, comparing it with the experimental data and it takes a long time. Therefore, it is preferable to use ready-made tools in the program.

2. **Numerical Research**

In order to obtain computation results that correspond to the theory, the simulation of an isotropy developed in the macro-volume is required. This could be done through a special simulation of cracks. One such simulation method is contact interaction between separate material volumes. In this case, the bended structure (for example: beam) is examined as a separate blocks set connected with contact interactions between each other. Contact pairs are located in places of assumed cracks.

In the process of such computational investigations, the reinforced concrete beam (length – 2 m, height of rectangular cross-section – 20 cm, and width – 10 cm) was examined. The concrete compression strength was taken as B25 in accordance with the reinforced concrete structures Code of Practice applicable in Russia. Hinged supports were taken. Reinforcement was taken in the form of two bars (diameter – 12 mm, A500 category) in accordance with the Code of Practice. The distance from the beam’s lower edge to the re-bars axis was 20 mm. Load that was uniformly distributed over the beam’s upper edge was applied.

![Figure 1. Model of the beam.](image)

In accordance with the Code of Practice, the maximum load for such a beam was 2.873 kgf/cm² (0.28 MPa), the height of the compressed zone was 6.78 cm, the force in each re-bar under the limit state was 4919.7 kgf (48.3 kN).

During the process of modeling, the beam 3D model was created. Solid185 elements and the Drucker-Prager Concrete material model for the concrete were used. Concrete properties during two- and three-dimensional stress state were taken based on the research of G.A. Geniev [1]. (Solid65 elements with a CONCR material model were also used – the results at that were almost same). Beam188 elements for bars were used. The dependence «σ-ε» for bars was taken in accordance with the Code of Practice. At that, diagram horizontal section instead of the section with a low growth (1%) was used. The dimensions of solid elements along the beam were 5 cm, height of section was 2 cm, width of section was 2.5 cm. Upper edge load was 3 kgf/cm², i.e. deterioration should occur at the 0.9658 value of the specified load.

The beam made of non-linear elements without creating contact pairs was initially calculated. The destructive load obtained was depending on the maximum concrete tensile strain taken for the material model. Thus, under maximum tensile strain corresponding to the Code of Practice, deterioration occurred at the load of 0.09 of the maximum one. Maximum tensile strains corresponding to the Code of Practice are related to those cases when concrete stresses are taken as equal to design strength and correspond to the yield line end in the «σ-ε» diagram. At that, falling branch «σ-ε» is not considered. With regard to the material model, the maximum tensile strain is designated while taking into
consideration the falling branch. Thus, the next analysis was done for concrete maximum tensile strains that twice exceeded the value in the Code of Practice. The result was slightly closer to the theoretical value. Maximum load was 0.145 of the maximum set value. At that, maximum concrete compressive stresses were 41 kgf/cm² (instead of 147 kgf/cm²), and the force in each re-bar was 432 kgf (instead of 4919 kgf). Thus, the deterioration did not correspond to reinforced concrete theory.

To obtain results corresponding to the theory, the beam concrete was divided into two parts in the middle, and contact interaction between these two parts was applied. This should simulate the crack formation.

The maximum load depended on the maximum concrete tensile strains taken for material model. When this value twice exceeded the Code of Practice value, the deterioration occurred at the load of 0.12 of the maximum value set in the calculation scheme. The stress state condition in the middle part of the model with a crack significantly deviated from the stress state in this place in the previous task. However, deterioration character was still not in compliance with the theory. An analysis of the results showed that strains in tensed concrete rapidly increase with the distance from the crack, and deterioration occurs alongside the crack when strains achieve ultimate values. This allows for outlining the following methods for achieving deterioration in accordance with the theory.

1. Divide beam into several short blocks connected with contact interactions. In this case, strains will have no time to achieve ultimate values in each block at a distance from the crack.

2. Increased maximum strains for tensed concrete can be taken for material model. In this case, the strains will not be exhausted until deterioration. This will result in some error with regard to the vertical movement calculation, but will also ensure that deterioration along the crack is obtained in strict accordance with the theory.

3. The use of non-linear elements in combination with contact elements only in the small medium section of the beam is possible. The other part of the beam should be elastic. Then tensile strains will have no time to achieve ultimate values at the short non-linear section with a crack, and elastic parts will prevent beam deterioration alongside the crack.

![Figure 2. Strains around the crack in non-linear beam.](image1)

![Figure 3. Stresses and appearance of cracks in the beams with elastic ends and non-linear middle parts of different length.](image2)
3. Main results
All the mentioned methods examined. The accuracy of the proposed approaches was completely confirmed. The results were obtained in strict accordance with reinforced concrete theory. This was related to maximum compression stresses, the height of the compressed zone, and bars forces.

For example, in the case of a completely non-linear beam with one contact section in the middle of the span with maximum concrete tensile strain 10 times exceeding the corresponding value of the Code of Practice, the deterioration occurred at a load 0.96 of the set value, i.e. the result was almost accurate.

![Stresses in concrete in the limit state](image1)

**Figure 4.** Stresses in concrete in the limit state are in strict accordance with the theory (method 2).

![Forces in reinforcement in the limit state](image2)

**Figure 5.** Forces in reinforcement in the limit state are in strict accordance with the theory (method 2).

When the short non-linear section is used, results depend on both length of the section and maximum tensile strain values taken. Thus, for a non-linear section with a length of 10 cm and
maximum tensile strain twice exceeding the value of the Code of Practice, the deterioration occurred at a load of 0.99 of the set value.

The obtained results make it possible to completely replace strength calculations of normal cross-sections as per the Code of Practice with FEM structural calculations.

4. Conclusion

The proposed method allows obtaining results in strict accordance with the theory of reinforced concrete. So the magnitude of the destructive load, the height of the compressed concrete zone, the stresses in the concrete and in the reinforcement in the limiting state fully correspond to the theory.

The obtained results make it possible to completely replace strength calculations of normal cross-sections as per the Code of Practice with FEM structural calculations.

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