Numerical study of the stress-strain state of reinforced concrete beam with pre-organized cracks under short-term and long-term loading

A Chhom
Novosibirsk State University of Architecture and Civil Engineering (Sibstrin), Novosibirsk, Russia
chhom_annoth@yahoo.com

Abstract. The article investigates the numerical modelling of deformation process and fracture of the reinforced concrete beams with preformed organized cracks and without preformed organized cracks under the action of short-term and long-term loading. Identified that, the features was changed of stress-strain state of beam during the deformation process and the main factors determining process of the fracture of beam. Effects from the introduction of organized cracks, observed in physical experiments, were confirmed by numerical experiment. Carried out of comparison analysis of the experimental data and the results of numerical modeling.

1. Introduction
Currently all over the world in the field of studying the features of reinforced concrete structures deformations to prevent the appearance of their cracks decrease the possible existing of width cracked. However, the experimental base for investigating the opening width cracked of reinforced concrete structures such as Gvozdev, N.I. Karpenko, V.M. Mitasov, I.N. Akhverdov, K.J. Willam, Z.P. Bazant and others. However, the problem is not completely solved and remains relevant to the present [1, 2]. Reinforced concrete structures were exposed to cracking not only under the action of short-term loading, but also under the action of long-term statically loading. Under the action of long-term statically loading in reinforced concrete structures are observed effect of the creep, which are closely related to the process of cracking. The mainly problem is to regulate the process of cracking of concrete considering of the creep. Solving this problem will improve the reliability of reinforced concrete structures and increase their service life.

Basic theory of resistance reinforced concrete provisions covered in the scientific work of Professor V.M. Mitasov [3, 4]. He represents fundamentally modern, non-traditional model of reinforced concrete distortion and destruction, energy version of reinforced concrete resistance theory have proposed the solution for transition state from solid cross-section into the cracks. The study is devoted to further improvement of rated cross-section method have used in classical theory of reinforced concrete resistance. For a basis of theoretical solutions of given model have taken the diagram-energy approach [5].

Nowadays, there are many modern mathematical modeling software products (ANSYS) [6], which provides a more completely and exactly information on the stress-strain state of reinforced concrete structures.
The purpose of work is to study the features of deformation reinforced concrete beams without organized cracks and with organized cracks under the action of short-term and long-term loading on the basis of experimental data and using the ANSYS Mechanical finite element method.

2. Problem setup
This work is related to numerical modelling process of deformation beam that were tested in experimental [7]. For carried out of research were prepared two series of beams such as cubes, prismatic. All elements have made the same composition of concrete, with singly reinforcement rebar and geometrical dimensions for every type of specimens. Beams were tested under short-term and long-term loading. All specimen have made from fine-grained concrete with strength the corresponding grade C20 ($f_c=11.5$MPa). Reinforcement rebar in grade A400 ($f_y=235$MPa), diameter 8 mm. Organized cracked formed installing galvanized steel plate, thickness 0.5 mm and height 20 mm at reinforcement rebar in maximum zone of bending moment. Beams in series 1; 2 calculated on concentrated load application force (F=800kgf) in center of beam. Singly reinforcement rebar, protection layer – 25 mm (Figure 1).

\[ \dot{\varepsilon}_{cr} = \left( C_1 \sigma^{C_2} (C_3 + 1) \varepsilon_{cr1} C_4 \right)^{1/(C_3 + 1)} e^{-C_4/T} \]

where $\dot{\varepsilon}_{cr}$ – strain rate of concrete creep; $\varepsilon_{cr}$ – strain of concrete creep; $C_1$, $C_2$, $C_3$, $C_4$ – creep measures of concrete, the values of which are determined from the experimental and taken as $C_1 = 1 \cdot 10^{-21}$; $C_2 = 2C_3 = 1,2; C_4 = 0$; T– temperature; $\sigma$ – equivalent stresses, MPa.

From the above equation it follows that the greater of the stress, higher the rate of development of creep strains. The rate of development of creep strains decreases with increasing accumulation of creep strains.
Most existing creep models take into account the dependence on the rate of development of creep strains on temperature. In this case, it is responsible for this parameter $C_4$. In the present of study, $C_4$ is assumed equal zero, and thus the temperature dependence is not considered. As noted in [9] in consideration of deformation of concrete beam is bigger, the greater dynamic effects are appeared in the formation of cracks occur (micro vibrations beam, the elastic waves). Thus, in consideration of creep model of temperature dependence maybe replaced by a similar type of dependence of the intensity of the dynamic effects.

3. Results and discussions

Numerical modeling of the process of deformation and fracture of reinforced concrete beams with pre-organized cracks and without pre-organized cracks under the action of short-term and long-term loads is performed using the ANSYS Mechanical finite element software. Selection of this software is due to the presence in it of a large number of universal mathematical models of inelastic deformation of concrete, in particular a model, as known by the acronym solid65, which is used the Wilama-Warnke limiting surface [10]. The solid65 model is phenomenological - the cracks occur in the surrounding is taken into account by changing its elastic characteristics. In solving the problem mainly used structured mesh (Figure 2) of the volumetric type solid65 finite elements of linear form functions. The characteristic size of the elements was 1-10 mm. The total number of nodes was $5 \times 10^4 \div 1 \times 10^5$.

![Figure 2. Finite element model of beam with pre-organized cracks.](image)

The organized crack was modeled as a break (discontinuity), i.e. a crack is introduced at the level of a geometric model and a finite element mesh. In order to reduce concentration of stress at the crack tip adopted fracture model with radius 1mm circle at the top.

Figure 3 shows fields of normal stresses $\sigma_x$. The axis of $x$ is directed along the beam axis. It shows only the right half of the beam, as the calculation is made using the symmetry properties of the structure.

In lowing of loads corresponding linear-elastic material working step ($F < 40$ kgf), the stress distribution in the beam is smooth in nature, without sharp discontinuities (Figure 3 a, b). With increasing load ($F > 200$ kgf) stress field becomes substantially non-uniform stresses appear sharp swings (Figure 3, c, d) due to the change in the stiffness at the sites of stochastic cracks.

In process of time, the stress field in concrete is changing (Figure 3 e; f), which is due to the development of creep strains and the appearance of new cracks. A strong change in stress was happened in the region of cracks. In the remaining regions, the stresses smoothly decrease in the process of time.

In Figure 4 shows the distribution of stochastic cracks for a beam without organized cracks under load $F = 200$ kgf. The crack was shown by red lines. Show only the right half of the beam because of its symmetry.
Figure 3. Normal of stress $\sigma_x$, Pa: (a) beam without organized cracks, $F = 40$ kgf; (b) beam with organized cracks $F = 40$ kgf; (c) beam without organized cracks, $F = 800$ kgf, in short-term loading $t = 30$ min; (d) beam with organized cracks $F = 800$ kgf in short-term loading $t = 30$ min; (e) beam without organized cracks, $F = 800$ kgf, in long-term loading $t = 86$ hours; (f) beam with organized cracks $F = 800$ kgf in long-term loading $t = 86$ hours.

Figure 4. Distribution of crack for a beam without organized cracks, $F = 200$ kgf.

Established that in a beam with an organized crack stochastic cracks were formed approximately in the same places as in a beam without organized cracks, however their height is lower in comparison with height of cracks in a beam without organized crack and their quantity is less approximately on 5 - 10%.

Figure 5 shows the dependence of deflection of beams without organized cracks and with organized cracks in process of time, obtained experimentally and by numerical modeling.
Figure 5. Dependence of deflection of beams without organized cracks and with organized cracks in process of time, obtained experimentally and by numerical modeling.

Beams without organized cracks, maximum deflection at the center point of the bottom face of the beam under short-term loading is 3.61 mm, and long-term loading - 3.92 mm; the growth in the deflection in 86 hours was 0.313 mm. Beams with organized cracks, maximum deflection at the center point of the bottom face of the beam under short-term loading is 3.14 mm, and long-term loading - 3.35 mm; the growth in the deflection in 86 hours was 0.21 mm. Thus, beams with organized cracks provided smaller deflection in the process under long-term loading, than beams without organized cracks.

Calculated dependence was shown in Figure 4, have a shape closely to the shape dependence obtained experimentally. At the initial moment of time, deflection was growth at a high velocity, and the process of time, the velocity of deflection was decreasing. That’s because of development during the time of creep strains; occur of stochastic cracks and accompanying redistribution of stresses. Graphic of beams with organized cracks is greater, if compared with the dependence of beam without organized cracks, due to lower intensity of development processes the creep of strains and cracks. In the case of beam with organized cracks, the discrepancy between the calculation results and the experimental data is the smallest and is less than 2.1%, and the beam without organized cracks, the discrepancy is much larger, but does not exceed 10%. In the calculations were obtained, the lower values deflections compared with deflection, determined in the experimental, in particular due to the fact that received mathematical model does not account for dynamic effects, which, as previously noted, is more strongly manifested in a monotonically increasing and under statically short-term loading.

Thus, the used phenomenological models of creep and inelastic deformation of concrete (solid65 model) can be used to simulate the process of deformation of beams with organized cracks under the action of long-term loading. However, the applied models of concrete deformation did not describe the change in the structure of the material during the deformation process. In addition, the used mathematical model does not account for the dynamic effects that significantly affect the process of cracking.

4. Conclusion
The possibility of using models creep of concrete, describing the work of a material with cracks (in particular, the solid65 model) for modeling the process of deformation of beams with organized cracks under the action of long-term loading.
The results of experimental data on the deformation of pre-organized cracks in the tensile zone of beam were confirmed by calculations of numerical modeling. Calculations showed that reinforced concrete beams with organized cracks in the tensile zone under the action of statically long-term loading have smaller deflections than beams without organized cracks.

Effects from the introduction of organized cracks into the tensile zone of beam observed in physical experiments are confirmed by a numerical experimental - calculations have shown that reinforced concrete beams with organized cracks in the tensile zone under the action of statically long-term loading have smaller deflections compared to beams without organized cracks.

The hypothesis is confirmed that the introduction of organized cracks into the tensile zone of beams under statically long-term loading was happened a redistribution of stresses and a decrease in the intensity of the cracks process and the accumulation of irreversible creep of strains. Justified application of practical significance creep models describing the work material with cracks for modeling deformation process with pre-organized cracks beams under long-term loading.

Acknowledgments
The research materials publishing was supported by the NSUACE (Sibstrin) internal grant #18-06.04.48 by 04.06.18.

References
[1] Purvis R, Babei K, Udani N, Qanbari A and Williams W 1995 Proc. 4th Int. Conf. Bridge Engineering (San Francisco, California) August 28–30 (Washington DC: National Academy Press) 163–75
[2] Stepanova I V 2004 New Res. Mater. Sci. Envir. 2 19–3
[3] Mitasov V M and Adishchev V V 2008 News Higher Educ. Ins. Construc. 13 222–7
[4] Mitasov V M and Adishchev V V 2010 News Higher Educ. Ins. Construc 6 3–8
[5] Mitasov V M and Adishchev V V 2010 News Higher Educ. Ins. Construc 5 3–9
[6] Marder M 2005 Phys. Rev. Let. 94 048001
[7] Mitasov V M and Chhom A 2017 J. Multidis. Eng. Sci. Techn 4 8494–96
[8] Bažant Z P 2001 Nucl. Eng. Design 203 27–38
[9] Xu X P and Needleman A 1994 J. Mech. Phys. Solids 42 1397–34
[10] Willam K J and Warnke E D 1975 Proc. Int. Ass. Bridge Struct. Eng. 19 174–91