Investigation of stress-strain state in the beam with preformed cracks

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Abstract. An experimental study of beams with preformed cracks using a polarization-optical method was carried out. Distributions of normal stresses in the vicinity of the crack were obtained. The zone of the edge effect is determined experimentally, as well as the character of the change in the neutral line near the crack. ANSYS is used to determine the stress-strain state in the vicinity of the crack. An original way of modeling a beam with preformed cracks was proposed. Numerical simulation data confirmed the experimentally obtained result on the independence of the length of the edge effect zone from the applied load.

1. Introduction
In recent decades, the problem of constructing an algorithm for "pass-through" calculation of bending reinforced concrete element was formulated and put in the form of a number of mathematical models of in the framework of the energy theory of resistance of reinforced concrete, proposed by V.M. Mitasov and V.V. Adishchev [1, 2]. The "pass-through" calculation assumes the calculation of the stress-strain state of the reinforced concrete element from the start of the loading and before the stabilization of the normal detachment cracks. To compose the energy relations closing the system of equations, it is necessary to know how the stress-strain state changes when a crack is formed, and also the extent of the so-called zone of the edge effect in the vicinity of the crack, in which the stress-strain state changes significantly. The zone of the edge effect is the characteristic region of the bent element in the vicinity of the crack, at which tangential stresses are significant, and a sudden change in the stresses in the longitudinal direction is observed. In the works of G.N. Albaut [3-5] it is noted that the neutral line after the formation of the crack has a wavy character, at a distance of about half the height of the beam to the left and to the right of the crack. In the present work the distributions of normal stresses in beams with preformed cracks were experimentally determined using the polarization-optical method [6-7] and the zone of the edge effect was determined.

2. Experimental study
Investigation of the stressed state of the bent reinforced element was carried out under conditions of pure bending (four-point bending) on a specimen with one crack 5 mm high, and also on a sample with three cracks 7 mm high (Figure 1 (a)). The width of the preformed cracks is 0.2 mm. The thickness of the samples – 6 mm, reinforcement percentage $\mu \approx 5\%$, the protective layer of the reinforcing element is not provided.
Samples are made of binder material – phenol-formaldehyde resin "Chromovinil-V 276", reinforcing layer – fiberglass "AG-4S". Ratio of limiting resistances \( R_{\text{armature}} / R_{\text{resin}} \) and moduli of elasticity \( E_{\text{armature}} / E_{\text{resin}} \) are equal:

\[
\frac{R_{\text{armature}}}{R_{\text{resin}}} = \frac{500 [\text{MPa}]}{40 [\text{MPa}]} = 12,5; \quad \frac{E_{\text{armature}}}{E_{\text{resin}}} = \frac{38000 [\text{MPa}]}{3200 [\text{MPa}]} \approx 11,87.
\]

Loading schemes and dimensions of the samples are shown in Figure 1 (b). Loading stage for each force \( F = 50 \text{ N} \). The maximum force \( F_{\text{max}} = 200 \text{ N} \).

Figure 1. A sample with three organized cracks: a general view (a); test circuit (b).

As a result of the experiment, using a polarization projection unit, patterns of interference bands (Figures 2 and 3) were obtained allowing estimating the edge effect zone. Residual (shrinkage) stresses were detected with the absence of a mechanical action \( F = 0 \text{ N} \) (Figure 2 (a)) in the section above the crack (cross-section 2-2) and at a distance of 15 mm from the crack (cross-section 1-1).

Figure 2. The pattern of interference bands and stress diagrams \( \sigma_x \) for a sample with one preformed crack at a load \( F = 0 \text{ N} \) (a), \( F = 200 \text{ N} \) (b).

According to the results of the experimental study, it was revealed that, the zone of the edge effect remains constant \( \approx 12 \text{ mm} \) with an increase in load (Figure 2). It was fixed the movement of the neutral line in the direction of the crack tip with increasing load. It is assumed that this change in the height of the zone compressed is possible due to the presence of residual stresses in the sample and (or) a large
percentage of reinforcement of the section. A similar result was recorded for a sample with three preformed cracks (Figure 3).

![Figure 3](image)

**Figure 3.** The pattern of interference bands and stress diagrams $\sigma_x$ for a sample with three preformed crack at a load $F = 0$ N (a), $F = 200$ N (b).

3. Numerical experiment

Numerical investigation of the stressed-deformed state of hinged-supported beams with preformed cracks (Figure 1) in three-dimensional setting in ANSYS is carried out.

The main difficulty of creating a geometric model and a computational grid in this problem is related to fracture modeling, caused by a small crack width of 0.2 mm in comparison with the remaining dimensions of the samples (Figure 4 (a)). This feature requires a grid thickening of up to 0.2 mm for a more accurate approximation of the geometry in the vicinity of the crack, which in turn will affect the increase in computation time.

![Figure 4](image)

**Figure 4.** The basic design scheme of the beam fragment in the vicinity of the crack: without the use of contacts (a); using bonded-type contacts (b).

To simplify the geometric model, the following method for modeling beams with pre-arranged cracks is proposed: by means of a rigid contact of the type bonded (Figure 4 (b)), which does not allow slippage and separation of interconnected surfaces [8], the beam is divided into two separate bodies, the gap between them corresponds to a crack width of 0.2 mm. The joint work of these bodies is provided due to the hard bonded bonds over the crack and between the reinforcing elements. Contact height crack is not provided. The advantage of this method of modeling is the possibility of co-building a single-type structured grid along the entire length of the sample, both in two-dimensional
and three-dimensional formulations. In this case a hexahedral grid with an element side of 1 mm was used.

Results of numerical simulation in ANSYS for samples with one and three cracks for sections 1-1 and 2-2 (Figures 2 and 3) are compared with experimental data, those are given below. Figure 5 shows the experimentally determined stress distributions in the longitudinal direction $\sigma_x$ ("Exp" lines), taking into account the effect of residual strains.

![Figure 5. Stress distribution in the longitudinal direction $\sigma_x$ for a beam with one crack in cross section height: 1-1 (a); 2-2 (b).](image)

The distribution of stresses in the longitudinal direction $\sigma_x$ along the height of the cross section of the beam differs little from the linear in the cross section 1-1 above the crack and over the entire height of the section 2-2 (Figure 5).

The results of calculations for beams with a preformed cracks obtained by numerical simulation ANSYS, showed good agreement between the calculated stress-strain state and the experimental data (Table 1). Numerical simulation data confirmed the experimentally obtained result on the independence of the length of the edge effect zone from the applied load.

In a sample with three preformed cracks, the height of the compressed zone is below the crack tip according to the results of the experiment and numerical simulation (Table 1). This allows us to conclude that the crack does not have a very significant effect on the stress state because of the high percentage of section reinforcement.

For beams with one and three cracks in figure 6 shows the strain $\varepsilon_x$ for different sections along the beam. The "peaks" in the section with the coordinate $u = 0$ mm correspond to the places where the load $F$ is applied to the upper surface of the beam (Figure 1). The black line with the note "crack" (Figure 6) is a longitudinal section along the beam in the level of the crack tip.

The red line (Figure 6) denotes the section of the "reduced neutral layer" – a cross section, along the length of which the strain approaches maximally to zero. The strain distribution near the "reduced neutral layer" in the vicinity of the crack has a curvilinear (wavy) character. When it is removed from the given layer (sections 6 mm and 0 mm), the strains are equalized.

4. Conclusion
Numerical modeling in ANSYS of beams with pre-arranged cracks is performed. An original way of modeling a beam in the vicinity of a crack with the help of a rigid contact of the bonded type is proposed.
Table 1. Comparison of calculated and experimental data at different loads.

| Parameter                                      | Beam with one crack | Beam with three crack |
|------------------------------------------------|---------------------|-----------------------|
| Zone of edge effect, mm                        | 12 12 11 11         | 12 12 11 11          |
| Normal Stress $\sigma_x$ (compressed area in section 1-1), MPa | -7.47 -14.93 -7.03 -14.07 | -7.47 -14.93 -7.03 -14.06 |
| Normal Stress $\sigma_x$ (compressed area in section 2-2), MPa | -7.47 -14.93 -6.98 -13.97 | -7.47 -14.93 -6.64 -13.28 |
| Normal Stress $\sigma_x$ (stretch area in section 2-2), MPa | 2.99 6.72 3.20 6.20 | 2.99 6.72 2.90 6.00 |
| Deflection of the compressed zone $X_R$ (section 1-1), mm | 14.29 13.79 13.52 13.52 | 14.29 13.79 13.83 13.83 |
| Deflection of the compressed zone $X_R$ (section 2-2), mm | 14.29 13.79 13.96 13.96 | 14.29 13.79 13.83 13.83 |

Figure 6. Distribution of strains in the longitudinal direction $\varepsilon_x$ for a beam: with one crack (a); with three cracks (b).
Comparing the experimental data with the results of calculations in the ANSYS for beams with pre-arranged cracks allow us to draw the following conclusions.

Numerical simulation data confirmed the experimentally obtained result on the independence of the length of the edge effect zone from the applied load, the difference from the experiment does not exceed 8%. The stresses \( \sigma \) in the vicinity of the crack, obtained with the help of numerical simulation, agree well (an error of 3-11%) with stresses determined experimentally.

Experimentally determined height of the compressed zone in the vicinity of the crack exceeds by 1-5% the height of the compressed zone, found by numerical modeling. Cracks do not have a significant effect on the distribution of longitudinal stresses and deformations in a bundle with three preformed cracks due to a high percentage of section reinforcement.

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