Deformation of intermediate zones of two-layers elements of reinforced concrete structures

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Abstract. Analytical dependences are constructed for a characteristic reinforced concrete element simulating inter-medium contact zones with simultaneously occurring processes of changing the long-term strength of concrete in time, taking into account the aging process of concrete and the process of neutralizing concrete with an aggressive environment. The proposed version of the calculation model of the long-term deformation of a corrosion-damaged composite reinforced concrete element in the zone of contact of two concretes makes it possible to study the deformed state of such structures in a plane stress state.

1. Introduction
For plane-stressed concrete and reinforced concrete structures operated in an aggressive environment, the wording and solution of the problem of the dynamics of changes in time of their strength and crack resistance [1-7] are very relevant. The results of these studies to this day continue to be the subject of discussion [1, 2, 8-11] regarding the differences in the approaches themselves to solving the problems of crack resistance, strength and deformability of cross-sections with the simultaneous manifestation of force and environmental influences. In this regard, given the long operational nature loading of reinforced concrete composite structures and the possibility of corrosion damage during their operation, it is of interest to develop a deformation model and criteria for the strength and crack resistance of the contact zone that of elements of composite plane-stressed reinforced concrete structures.

2. Calculation model
The constructed model is based on the theory of deformation of highly stressed reinforced concrete with cracks N. I. Karpenko [11, 12]. According to this model, the relationship of stresses and strains of a characteristic element is presented in the form:

\[
\begin{pmatrix}
\varepsilon_x \\
\varepsilon_y \\
\gamma_{xy}
\end{pmatrix} =
\begin{bmatrix}
C_{14} & C_{12} & C_{15} \\
C_{12} & C_{22} & C_{23} \\
C_{15} & C_{23} & C_{33}
\end{bmatrix}
\begin{pmatrix}
N_x \\
N_y \\
N_{xy}
\end{pmatrix},
\]

(1)
where $\varepsilon_x, \varepsilon_y, \gamma_{xy}$ are deformations, $N_x, N_y, N_{xy}$ are axial and shear forces in in a characteristic plane-stressed element of unit dimensions, $C_y$ are the coefficients of the compliance matrix of reinforced concrete.

Figure 1. Scheme of forces in a typical plane-stressed reinforced concrete element for calculating the deformation of the inter-medium contact zones of the elements of composite structures.

When cracks form in the characteristic element under consideration in two directions — in the direction of the contact seam and in the direction of the main tensile forces (Figure 1), the concrete loses its ability to independently absorb forces. In this case, only some concrete bonds between the edges of the cracks are preserved and the ability of the concrete in the areas between the cracks to resist the tangential movements of the reinforcing bars crossing the crack remains.

When a longitudinal crack is formed in the area of the inter-medium contact of two concrete and a crack from the main tensile forces, all the forces acting in the characteristic element are transferred to the reinforcement (Figure 2).

![Figure 2](image)

Figure 2. Scheme of efforts in the reinforcement after the formation of cracks in a characteristic element.

The coefficients of the compliance matrix $[C_{ij}]$ for finite elements with cracks in the zone of inter-medium contact of two concretes and cracks from the main tensile forces of a flat element at stress and strain increments are determined from the expressions:
where the coefficients of equations (2) are determined by the formulas:

\[
\begin{align*}
A_1 &= \left(-\sqrt{2}/4E'_{xy}\mu\right)E_{xy} + \left(-\sqrt{2}/4E''_{xy}\mu\right)E_{xx'y'} + \\
&\quad + \left(\sqrt{2}(\sin 3\beta - 2\sin(3\beta/2)^2 - 2 \sin(\beta/2)^2 + \\
&\quad + \sin \beta + 2)/4E'_{xy}\mu(2 \sin(\beta)^2 - 2)\right)E_{yy'} + \\
&\quad + \left(\sqrt{2}(\sin 3\beta - 2\sin(3\beta/2)^2 - 2 \sin(\beta/2)^2 + \sin \beta + \\
&\quad + 2)/4E'_{xy}\mu(2 \sin(\beta)^2 - 2)\right)E_{yy'y'} - \left(\sqrt{2}(\sin(\pi/4 + 3\beta) - 4 \sin(\beta)^2 - \\
&\quad - 4 \sin(\beta/2)^2 + \sqrt{2}\sin(\pi/4 + \beta) + 6)/8\mu(\sin(\beta)^2 - 1)\right), \\
A_2 &= \left(-\sqrt{2}/4E'_{xy}\mu\right)E_{xy} + \left(-\sqrt{2}/4E''_{xy}\mu\right)E_{xx'y'} + \\
&\quad + \left(-2\sqrt{2}\cos \beta^2 - 2\sqrt{2}\cos \beta \sin \beta /4E'_{xy}\mu \cos \beta\right)E_{yy'} + \\
&\quad + \left(2\sqrt{2}\cos \beta \sin \beta - 2\sqrt{2}\cos \beta^2 + 2\sqrt{2}/4E'_{xy}\mu \cos \beta\right)E_{yy'y'} + \\
&\quad + \left(\cos \beta - \sin \beta + 1\right)/2\mu, \\
A_3 &= \left(\cos \beta + 1\right)/\mu, \\
B_1 &= \left(\sqrt{2}/4E'_{xy}\mu\right)E_{xy} + \left(\sqrt{2}/4E''_{xy}\mu\right)E_{xy'y'} + \\
&\quad + \left(-\sqrt{2}(\cos 2\beta - \sin 2\beta)/4E'_{xy}\mu \cos \beta\right)E_{yy'} + \\
&\quad + \left(-\sqrt{2}(\cos 2\beta - \sin 2\beta)/4E'_{xy}\mu \cos \beta\right)E_{yy'y'} + \\
&\quad - \left(\sqrt{2}(2E'_{xy}/2 + E'_{xy}\sin\left(\frac{\pi}{4} + 2\beta\right) + \sqrt{2}E''_{xy}\cos \beta)/4E'_{xy}\mu \cos \beta\right)\right)
\end{align*}
\]
(3)

where $l_{rc}$ is the size of the zone of relative mutual displacements of concrete and reinforcement in the area adjacent to the crack:

$$E'_{sy} = E_s / \psi_{st}$$

(4)

$E_s$ is the modulus of elasticity of the reinforcement, $\psi_{st}$ is the averaging coefficient of V.I. Murashov $\eta_\tau$ is the coefficient taking into account the increased flexibility of the reinforcing bars with tangential displacements.

The presented analytical dependences make it possible to construct the compliance matrix $[C_{ij}]$ of a corrosion-damaged long-deformable reinforced concrete element with cracks. The change in time of the deformative properties of concrete neutralized by an aggressive environment during matrix formation $[C_{ij}]$ can be taken into account by changing the reduced tangential modulus of deformation in time:

$$E^k_{h}(t) = \nu^k_h \cdot E^*_h(t)$$

(5)

where $E^*_h(t)$ the dependence of the change in the modulus of concrete deformation on time due to the influence of an aggressive environment at the considered time $t$; $\nu^k_h$ is the coefficient of change of the tangent modulus of concrete strips between cracks determined by the analytical dependences of the description of concrete deformation diagrams, expressed in terms of deformation levels $\eta_d$ and stresses $\eta$.

$$E_{sy}^*(t) = E_{h}^*(t) \varphi, \quad E_{sy}^*(t) = E_{h}^*(t) \varphi$$

(6)

where $E_{h}^*(t)$ is the dependence of the change in the modulus of concrete deformation over time due to exposure to an aggressive environment.

3. Conclusions

The proposed deformation model allows a fairly rigorous analysis of the long-term deformation of loaded reinforced concrete plane-stressed composite structures, taking into account the complex stress state in these zones and at the same time the manifestation of parallel aging processes of concrete in time and its neutralization by an aggressive environment.

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