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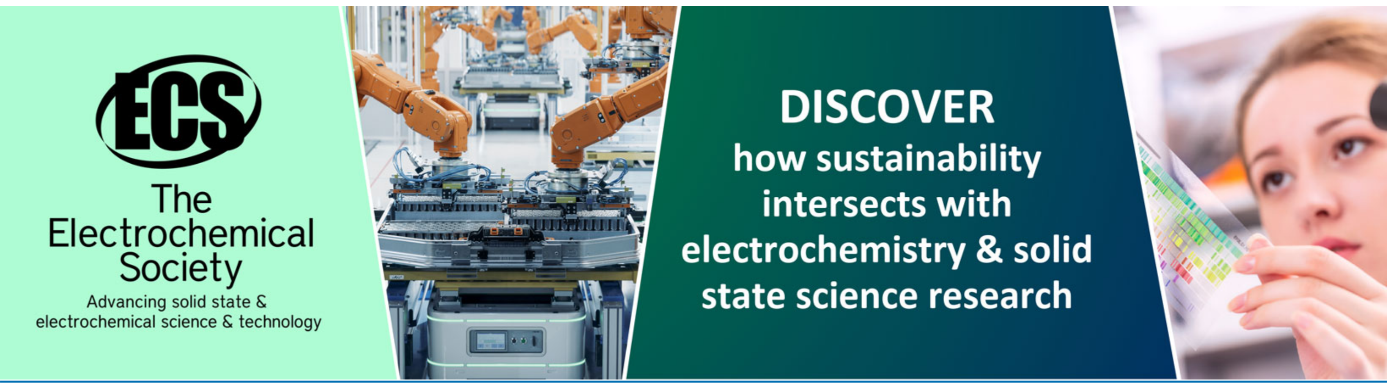

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Numerical modeling of concrete deformation processes during its interaction with reinforcement

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Abstract. The aim of the work is to propose a numerical model of the interaction of reinforcement with concrete in order to be able to simulate the operation of structures of building and transport facilities. In the course of the study, the authors carried out a numerical simulation of the processes of deformation of concrete during its interaction with reinforcement; a model was implemented based on linear connections with finite rigidity. The results of the calculation were compared with the experimental data, the dependence "pulling force - reinforcement slipping relative to concrete" was constructed.

1. Introduction

The interaction of concrete and reinforcement in the operation of reinforced structures occurs due to various factors [1, 2], such as: mechanical engagement of reinforcement for concrete, friction between concrete and reinforcement, molecular interaction, etc. The processes of complex interaction between concrete and reinforcement are characterized by the curve of the dependence of "adhesion stress - slippage of reinforcement relative to concrete", or the alternative relationship "pulling force — slippage of reinforcement relative to concrete" [3, 4, 5]. Such a curve can be constructed using the experimental method of pulling the rod out of the cube (Pull-out test) according to RILEM / CEB / FIB [3, 6].

There are several classes of models of adhesion of concrete and reinforcement [2], such as: the model of the ideal adhesion of reinforcement and concrete; model with the addition of an additional layer with a reduced strain modulus; a model using finite stiffness bonds; model with the shutdown of destroyed items from work; microcracking model; elastic material model; model of elastic-plastic-damaged material. The most common are the first three models, the other models require high-level software packages, like ANSYS, Nastran, ABAQUS, and others.

The model of ideal adhesion of reinforcement and concrete is consistent in the evaluation of structural strength, but is unacceptable in the evaluation of structural deformation.

The model with the addition of an additional layer with a reduced initial modulus of deformation requires a more detailed discretization of the computational model, namely, the use of bulk finite elements with a small grid breakdown for concrete, reinforcement and the boundary layer itself, which is not allowed for calculating complex computational schemes, as it will require large time costs.

The model based on the use of bonds with finite stiffness is considered the most logical, and also has the greatest consistency with the experimental and theoretical results of adhesion of metal reinforcement to concrete [2]. This model allows to take into account non-linear displacements of reinforcement relative to concrete in the process of destruction of cohesion bonds. For the numerical description of the model, it is required to introduce additional elements with finite stiffness or otherwise flexible connections.

To describe the processes of deformation of reinforced concrete, various numerical methods and analytical methods are used [7-17]. In this paper, within the framework of the finite element analysis, a numerical model of adhesion of concrete to reinforcement was proposed based on linear connections with finite rigidity. In order to take into account the possibility of slippage and separation of reinforcement in concrete, a contact interaction technique is implemented, a special contact end element with specific properties [18, 19] is constructed, which simulates a contact layer on the surface of interaction between concrete and reinforcement.

2. The mechanism of contact interaction of reinforcement and concrete

The mechanism of interaction between reinforcement and concrete between them can be illustrated by Figure 1, which shows one of the options for deforming the contact layer, for greater clarity, formed by two plates.

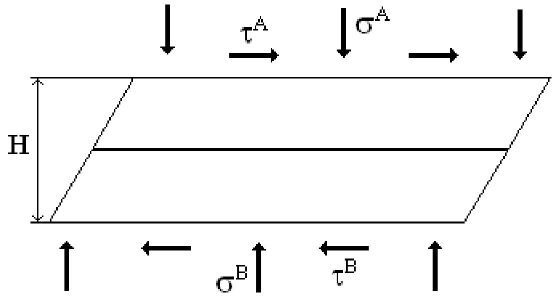

Figure 1. Schematic of contact interaction between reinforcement and concrete.

For a situation when compression $\sigma_H = \sigma^A = \sigma^B$ and strain $\varepsilon_H = \sigma_H / E_H$ occurs in the lining, where E_H is the modulus of elasticity of the lining material. The geometrical condition for the presence of this situation is $H \le \left(H^A + H^B\right)$, where, H^A, H^B - the initial thickness of the plates, H - the distance between the surfaces on which they are fixed.

With precompression, i.e. at $H < \left(H^A + H^B\right)$, and, in this case, also true

$$\sigma_H = \sigma^A = \sigma^B, \varepsilon_H = \sigma_H / E_H .$$

If the force is absent or too small and the lining moves freely, then

$$H \ge \left(H^A + H^B\right), \sigma_H = 0.$$

If free slip is realized, in which the tangential stresses do not occur, which is realized when $H \ge \left(H^A + H^B\right)$, and in this case $\tau_H = 0$.

Elastic interaction with compression and shear without slippage is possible when $H \le \left(H^A + H^B\right)$ and for stresses and strains in the lining can be written

$$\sigma_H = \sigma^A = \sigma^B, \tau_H = \tau^A = \tau^B, \varepsilon_H = \sigma_H / E_H, \gamma_H = \varepsilon_H = \tau_H / G_H .$$

An additional condition here should be the condition

$$\tau_H \le f \left|\sigma_H\right|, \quad (1)$$

where f - friction coefficient.

At default (1) there is a situation when there is a shift of overlays with slipping. In this case

$$\sigma_H = \sigma^A = \sigma^B, \tau_H = \tau_{np} = f \left|\sigma_H\right|, \varepsilon_H = \sigma_H / E_H$$

and there is slippage. All these situations can be simulated within the framework of continuum mechanics, i.e. in the presentation of two plates in the form of a single material with specific properties.

The resulting problem is non-linear and requires the use of special techniques to solve it. A characteristic feature of this nonlinearity is that for normal stresses there are limitations on the deformation ($H \le H^A + H^B$, mutual deformation of the linings can not be greater than their total thickness), and for shear stresses, by their limiting values, which determine the possibility of slipping.

The general resolving equation is written in a variation form based on the principle of virtual displacements

$$\sum_m \iiint_{\Omega_m} \{\sigma\}^T \{\delta\varepsilon\} d\Omega + \sum_k \iiint_{\Omega_k} \{\sigma_H\}^T \{\delta\varepsilon_H\} d\Omega = \sum_m \left(\iiint_{\Omega_m} \rho \{g\}^T \{\delta V\} d\Omega + \iint_{S_m^\sigma} \{P\}^T \{\delta V\} dS \right),$$

where the sum on m - the sum on volumes of blocks, on k is designated the sum on slips, Ω_m, Ω_k - accordingly volumes of blocks and slips; $\{\sigma\},\{\varepsilon\},\{V\}$ - stresses, deformations and displacements of elementary volumes of blocks; $\{\sigma_H\},\{\varepsilon_H\}$ - stresses and strains in the plates, $\{g\}$ - the vector of gravitational acceleration ($\rho\{g\}$ - gravity), $\{P\}$ - the boundary load acting on a part of the boundary S_m^σ. The algorithm for solving the problem of elastoplastic deformation, is implemented within the framework of the finite element discretization of the computational domain.

3. Numerical example

On the basis of the proposed technique, a full-scale experiment of studies of the adhesion of reinforcement to concrete was recreated. The design model of the experimental sample consisted entirely of bulk finite elements, the characteristics for concrete were set for class B 30, the strain modulus for fiberglass reinforcement was 55000 MPa, the calculated compressive resistance 800 MPa with ultimate relative deformations 0.0035. The problem was solved by a step method in a nonlinear formulation, with a final load of 6 kN. The simulation results are presented in Figure 2, which also shows the diagrams of "pulling force - slippage of reinforcement relative to concrete" obtained from the results of the experiment and according to the method proposed in [20].

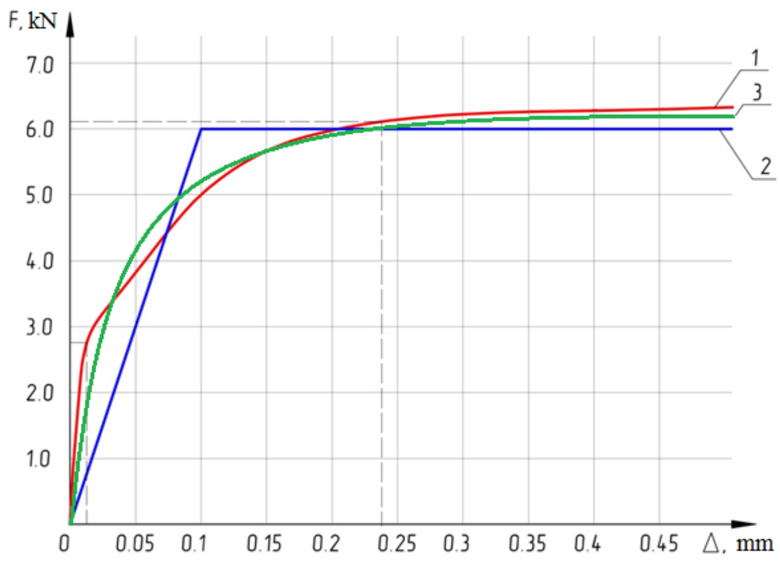

Figure 2. Graphs of the dependence of the movement of fiberglass reinforcement Δ on the pulling force F, 1 - according to the test results; 2 - for numerical simulation from [20]; 3 - according to the proposed method.

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4. Analysis of the results and conclusions

Analysis of the obtained values shows that in addition to the deformation and the subsequent rupture of the bonds themselves, there are deformations of the concrete of the boundary zone. When solving a specific task, it is necessary to solve test problems that will allow to determine the value of the required number of bonds simulating the reinforcement adhesion to concrete with the required accuracy. According to the results of the experiments performed on the samples, a “pulling force — reinforcement slippage” diagram of “sandy” composite reinforcement with a diameter of 6 mm relative to concrete was constructed. For numerical modeling of composite reinforcement adhesion to concrete, a model is proposed based on destructible linear connections with extreme stiffness, which showed good convergence in modeling adhesion of metal reinforcement to concrete.

Acknowledgments

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