FEM Simulation of Reinforcing Plain Bar Pull-Out Test from Concrete Sample

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Abstract. The paper presents results of 3D numerical modeling and calculations of a plain bar Ø16 mm concreted in the concrete cube during pull-out test. The prepared geometry reflected real sample dimensions. The mechanical parameters of the materials and assumptions for analysis were adopted based on the results obtained from the experimental tests previously carried out. Numerical calculations included non-linear finite element method (FEM) analysis. As a result of numerical calculations, it was possible to trace the deformation state, stresses and cracking as well as their development along with the change of the bar displacement in the sample. The increase of strains and stresses into the concrete sample occurred until the maximum value of the concrete-steel bond in accordance with the bond model was achieved. After exceeding the top, there was a constant decrease in strains and stresses in concrete with the increase in displacement of the bar (with extension). The first cracks appeared at a slip of approximately 0.1 mm. Cracking of concrete progresses with the increase of the bar displacement in relation to the concrete.

1. Introduction
The purpose of the FEM numerical analyzes was to create a computer model of a concrete bond to a plain reinforcing bar Ø16 mm. The 3D model was used to obtain information on the concrete stress and strain distribution inside the concrete cube in the immediate vicinity of the reinforcement at the moment of loss of adhesion and the image of the internal cracking of concrete during the tests.

The assumption of the analyzes was to map the pull-out destructive tests in the FEM software in order to obtain a complete image of the test course and to supplement the results of the experimental tests with the description of internal destructive mechanisms.

2. Experimental base and material model
The experimental tests were carried out on concrete samples with dimensions of 160×160×160 mm with an axially placed reinforcing bar. The tests were performed for the active bond lengths of 40, 80 and 120 mm (the remaining length was excluded from adhesion by means of a plastic casing - pipes Ø20 mm) on days 1, 3, 7, 28 and 90 of concrete maturation. The results of material research and pull-out tests [1] were used to build a numerical model, define the input parameters and calibrate the FEM model.

The article presents an analysis performed for samples matured for 24 hours and with an active length of 120 mm.
2.1. Concrete
A nonlinear model of the isotropic concrete material was adopted based on the Total Strain Crack Model [2, 3]. In terms of tension, the description of the material was adopted by the LINEAR function, and for compression by the CONSTA function (fig. 1).

![Total Strain Crack model](image)

**Figure 1. Total Strain Crack material model for concrete in tension and compression**

Mechanical properties of concrete experimentally determined after 1 day of maturation were used for the numerical analysis. The adopted concrete properties are included in table 1.

| Age of concrete [days] | f_{c,cube}^a [MPa] | f_{c,cyl}^b [MPa] | f_{ct}^c [MPa] | E_{cm}^d [GPa] | v^e [-] |
|------------------------|--------------------|-------------------|---------------|----------------|--------|
| 1                      | 47.5               | 40.2              | 3.0           | 35.9           | 0.286  |

*a Concrete compressive strength determined on cubic samples of 15×15×15 cm, b Concrete compressive strength determined on cylindrical samples of Ø15×30 cm, c Axial tensile strength of concrete, d Modulus of elasticity, e Poisson’s ratio (theoretical value)*

2.2. Reinforcing steel – Ø16 mm bar
A nonlinear model of the isotropic bar material was adopted based on the Von Mises model with Multi-Linear Hardening after yielding [3]. A diagram of hardening is shown in figure 2.

![Strain hardening](image)

**Figure 2. Definition of strain hardening**

The assumed mechanical properties of the reinforcing steel for numerical analysis are included in table 2. The strain hardening parameters were defined as shown in figure 2 and shown in table 3. The properties of the reinforcing steel were experimentally determined in a static tensile test.

| E^a [GPa] | v^b [-] | f_y^c [MPa] |
|-----------|---------|-------------|
| 207.3     | 0.3     | 304.4       |

*a Modulus of elasticity, b Poisson’s ratio, c Yield strength*
Table 3. Parameters of strain hardening of steel for FEM calculations

| index | $\kappa^a$ [-] | $f^b$ [MPa] |
|-------|----------------|------------|
| 0     | 0              | 304.4      |
| 1     | 0.03           | 317.9      |
| 2     | 0.11           | 440.5      |
| 3     | 0.28           | 465.1      |

$^a$ Steel strain, $^b$ Steel stress

2.3. Interface element

User define Multi-Linear model was the base for FEM calculations [3]. In the model, the basic parameters of the interface material were as shown in table 4.

Table 4. Interface stiffness for FEM calculations

| $K_n^a$ [kN/m$^3$] | $K_t^b$ [kN/m$^3$] |
|---------------------|---------------------|
| $2.6 \times 10^{11}$| $2.6 \times 10^{10}$|

$^a$ Normal stiffness modulus, $^b$ Tangential stiffness modulus

The definition of the coefficients of the Multi-Linear function for individual model is based on the relationships from figure 2. The parameters of the function for the model of concrete-steel bond after 1 day of maturation are shown in table 5, while their functions are shown in figure 3.

Table 5. Multi-Linear function coefficients for FEM calculations

| $\Delta u_n^a$ [mm] | 0 | 0.1 | 0.4 | 1.5 | 3.5 | 10 |
|---------------------|---|-----|-----|-----|-----|----|
| $t_n^b$ [MPa]       | 0 | 5.3 | 6.8 | 6   | 5.3 | 4.4|

$^a$ Relative displacement (slip), $^b$ Shear traction (tangential stress)

The functions were designed, the scope of which corresponded to the experimental tests performed earlier. The values of the tangential stress $t_n$ and the slip $\Delta u_n$ adopted for the model were calculated as average values from the experiment on samples tested after 1-day of maturing concrete. The function adopted for the FEM model is presented with a solid line, while the development of the average bond stress determined in experimental tests is presented with a dotted line [1].

Figure 3. Designed Multi-Linear function for FEM calculations
3. FEM model
A 3D numerical model of a bar concreted in a cube was made. The geometry of the model, boundary and initial conditions are shown in figure 4. The prepared geometry reflected with real sample dimensions. The concrete cube is 160×160×160 mm. A reinforcing bar was axially positioned (concreted) inside the cube. The total length of steel reinforcement is 250 mm. Calculations were made for the length of active adhesion 120 mm. The remaining section excluded from adhesion by Ø20 mm tube was implemented as a free space in the numerical model. Boundary conditions were created by roller supports - blocking the movement for the vertical direction - applied to the entire lower surface of the concrete sample. The load to the model was implemented in the form of displacement applied to the lower end of the steel reinforcement (from the side excluded from adhesion).

Figure 4. Geometry of the 3D model of pull-out test

4. Description of the model
The geometry of the model is shown in figures 5 and 6.

Figure 5. Numerical model of the sample: a) vertical cross-section, b) 3D view
4-node solid elements for the bar and concrete and 3-node plane elements with zero thickness for the contact (interface) surface were assumed. The maximum dimension of the element was set at 3 mm. The convergence of the solution was checked for a mesh with maximum dimensions of 6 and 3 mm. The obtained results were satisfying. The model of the concrete cube with a steel bar consists of 217,236 nodes and 868,944 finite elements.

The non-linear numerical analysis using the Finite Element Method (FEM) included calculations in the scope of:
- nonlinear statics,
- nonlinear material behaviour of concrete and steel,
- nonlinear interface (contact) behaviour.

5. Results
Due to the multitude of results, with their similarity and repeatability, it was decided to include in FEM calculations only the selected samples. The FEM analysis refers to the 1-day age samples with an active bond length of 120 mm. Below are the results obtained from computer analyzes for the sample load condition at the bar slip of 0.1 mm, 0.5 mm and for the final bar pull-out condition at the slip of 10 mm.

Figures 7 and 8 show the distribution of the main strains in the sample during the pull-out test. Figures 9 and 10 show the development of cracking and micro-cracking of the sample.

6. Conclusions
As a result of numerical calculations, it was possible to trace the deformation state, stresses and cracking as well as their development along with the change of the bar displacement in the sample. During the test, there was a complex state of strain and stress in the sample. The increase of strains and stresses into the concrete sample occurred until the maximum value of the concrete-steel bond in accordance with the bond model was achieved [1, 4]. After exceeding the top, there was a constant decrease in strains and stresses in concrete with the increase in displacement of the bar (with extension). During the test, the concrete inside the cube cracked. The first cracks appeared at a slip of approximately 0.1 mm. It was found that the cracking initiation speed in the model depends on the size of the finite elements and the size of the calculation step (interval). Cracking and micro-cracking of concrete were initiated at the end of the excluded section (in the immediate vicinity of the void for tube) and with the increase in the value of slip spreads along the rod along the active length. When the maximum bond reached its further increase in rod extension, the image of internal cracking practically does not change.
Figure 7. Total strains: a) $\varepsilon_1$, b) $\varepsilon_2$, c) $\varepsilon_3$, with bar slip of 0.1 mm
Figure 8. Total strains: a) $\varepsilon_1$, b) $\varepsilon_2$, c) $\varepsilon_3$, with bar slip of 0.5 mm.
Figure 9. Internal cracking of concrete with bar slip of 0.1 mm

Figure 10. Internal cracking of concrete with bar slip of 0.5 mm

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