FEM Analysis of Bond between Concrete and Seven-Wire Prestressing Strand

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Abstract. Detailed FEM analysis of the pull-out test of seven-wire prestressing strand form concrete sample is the purpose of the article. A 3D numerical model of a seven-wire prestressing strand concreted in the concrete cube was made. The assumption of the most trusted modeling of the strand geometry for numerical calculations was assumed. The mechanical parameters of the materials and interface elements for analysis were adopted based on the results obtained from the experimental tests previously carried out by the author. 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 strand displacement in the sample. The images of deformations and stresses in the sample confirmed theoretical considerations and suppositions from experimental tests about its accumulation of the largest values in longitudinal concrete wedges in the closest cover of the strand. During the test, the concrete inside the cube cracked quickly. The first cracks appear in the zone of the nearest cover of the strand. Numerical analysis made it possible to observe both the failure mechanisms identified in the experimental tests. The first mechanism consisted in cutting the longitudinal concrete wedges between the individual wires. The second mechanism was based on the rotation of the strand and its slip along the route of the twist.

1. Introduction
Performing experimental tests of the pull-out bond of concrete to prestressing strands allow to determine the value of the pull-out force in relation to strand displacement in the sample. Such a function can also be obtained by performing bond tests with other well-known methods [1, 2]. The obtained result of tests experienced from an engineering point of view is sufficient - it allows to determine the average bond stress as well as to determine the prestressing force transfer length. From the scientific point of view, this can be only a contribution to further analysis. The results of destructive tests do not give the full picture of the phenomenon. It is not possible to record the state at every certain point of the sample during the test. The solution may be FEM numerical analyzes - which allow to look deep inside the sample [1, 3].

The purpose of the FEM numerical analyzes was to create a computer model of a concrete bond to a seven-wire prestressing strand 7Ø5 mm. The 3D model was used to obtain information on the concrete stress and strain distribution inside the concrete cube, as well as 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 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 [1].
2. Model conception and assumptions
Initially, it was assumed that the sample geometry is as accurate as possible. During the implementation of the task, several difficulties and limitations were encountered, which unfortunately verified the initial assumptions. For this reason, it was decided to:

- model the strand as a single solid bar,
- reduce the dimensions of the sample for analysis.

A replacement concrete cube with dimensions of 50×50×25 mm was adopted. Inside the sample, the strand was axially positioned (concreted). The strand cross-section geometry has been retained with the actual dimensions, while the sidewall has been modified. The full-twisting period of the outer wires relative to the middle wire was shortened from 250 to 50 mm. The total length of the weave in the model is also 50 mm. In the numerical model, sections excluded from adhesion were not used, that is why the modeled active length represents 12.5 cm in reality (half of the actual twisting period of the outer wires in the strand). Boundary conditions were created by roller supports - blocking the movement for the vertical directions - applied to the entire upper surface of the sample concrete. The load to the model was implemented in the form of displacement applied to the upper end of the steel reinforcement (strand).

3. FEM model description
The geometry of the model of strand is shown in figure 2, the geometry of the entire model is shown in figure 3. Contact surface, and thus the interface elements took the shape of the strand skin (fig. 4).
4-node solid elements for the strand 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 1 mm. The model of the concrete cube with a steel strand consists of 84,994 nodes and 339,936 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.

4. Założenia i modele materiałowe

FEM analysis was performed for the mechanical properties of materials obtained from experimental tests. The analysis covered samples with 705 mm strand without initial prestressing, tested after 1 day of concrete maturation [1].

4.1. Concrete

A nonlinear model of the isotropic concrete material was adopted based on the *Total Strain Crack Model* [4, 5]. The adopted concrete properties are included in table 1.
Table 1. Concrete properties for FEM calculations [1]

| Age of concrete [days] | $f_{c,\text{cube}}^a$ [MPa] | $f_{c,\text{cyl}}^b$ [MPa] | $f_{ct}^c$ [MPa] | $E_{cm}^d$ [GPa] | $\nu^e$ [-] |
|------------------------|-----------------------------|-----------------------------|-----------------|-----------------|-------------|
| 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)

4.2. Prestressing steel – 7Ø5 mm strand

A nonlinear model of the isotropic material was adopted based on the Von Mises model with Multi-Linear Hardening after yielding [5]. The assumed mechanical properties of the prestressing steel for numerical analysis are included in table 2. The strain hardening parameters are shown in table 3.

Table 2. Prestressing steel properties for FEM calculations [1]

|   | $E^a$ [GPa] | $\nu^b$ [-] | $f_{p0.1}^c$ [MPa] |
|---|-------------|-------------|-------------------|
|   | 207.3       | 0.3         | 1678.6            |

* $a$ Modulus of elasticity
* $b$ Poisson’s ratio
* $c$ 0.1 % proof-stress of prestressing steel

Table 3. Parameters of strain hardening of steel for FEM calculations

| index | $\kappa^a$ [-] | $f^b$ [MPa] |
|-------|----------------|-------------|
| 0     | 0              | 1678.6      |
| 1     | 0.04           | 1906.8      |

* $a$ Steel strain
* $b$ Steel stress

4.3. Interface element

The user-defined Multi-Linear model was the base for FEM calculations [5]. 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 concrete-steel bond model (based on test results) are shown in table 5, while the functions are shown in figure 5.

Table 5. Multi-Linear function coefficients for FEM calculations

| $\Delta u_n$ $^a$ [mm] | $t_n$ $^b$ [MPa] |
|-------------------------|-------------------|
| 0                       | 0                 |
| 0.1                     | 3.2               |
| 1                       | 5.8               |
| 2                       | 5.1               |
| 4                       | 5.0               |
| 8                       | 5.0               |
| 10                      | 5.3               |

$^a$ 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 experimental test. 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].

5. Results

Figure 6 shows the distribution of the total strains in the sample during the pull-out test. Figure 7 shows a picture of the development of cracking in the sample during pulling out of the strand. Figure 8 shows the sample deformation vectors during the load test.
Figure 6. Total strains: a) $\varepsilon_1$, b) $\varepsilon_2$, c) $\varepsilon_3$, with strand slip of 0.1 mm
Figure 7. Internal cracking of concrete with strand slip of 0.1 mm

Figure 8. Image of displacement vectors at 2.5 mm slip

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 strand displacement in the sample. During the test, there was a complex state of strain and stress in the sample. The images of deformation and stress in the sample confirmed theoretical considerations and suppositions from experimental tests about its accumulation of the largest values in longitudinal concrete wedges in the closest cover of the strand [1, 2]. During the test, the concrete inside the cube cracked quickly. The first cracks appeared in the zone of the nearest cover of the strand.
The numerical analysis made it possible to observe both the failure mechanisms identified in the experimental tests. The first mechanism consisted of cutting the longitudinal concrete wedges between the individual wires. The progress of micro-cracks and cracks spreading inside the concrete cube confirms this process of bond destruction. The second mechanism was based on the rotation of the strand and its slip along the route of the twist. The presented vector image of the strand and concrete sample displacements in the numerical model from the pull-out load (defined displacement along the strand axis) clearly confirms the phenomenon. The concrete cube model shows the opposite rotation to the strand. The displacement vectors cover a 360 ° range around an axially oriented strand in the sample.

Performed numerical FEM analysis allows to understand the destructive mechanisms occurring in the 705 mm strand pulling test. Additionally, it is possible to catch the local values of internal forces, deformations, cracks and micro-cracks at any point in the sample, both in steel and concrete.

References
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