EXPERIMENTAL INVESTIGATIONS AND MODELING OF BOND BETWEEN ROUND STRAND ROPES AND CONCRETE

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ABSTRACT

This contribution presents research work on the bond behaviour of in concrete embedded one-layered round strand ropes 6 x 19 Standard. The essay reports about experimental tests and theoretical modeling of the embedded wire ropes.

The investigation on the bond of embedded steel wire ropes is based on already available knowledge about pure steel wire ropes and the bond behaviour of conventional types of reinforcement. The affinity of bond behaviour of reinforcing steel bar and prestressing strands are used to develop a new material model.

Experimental tests are the base of modeling. Global bond behaviour was analysed by RILEM-pull-out tests. The tests studied the influence of concrete strength, rope geometry and bond length. Thereby the usual setup was modified to account for the special properties of the ropes. Another testing series showed the material behaviour of the cement paste penetrated wire rope. It‘s possible to describe the strain behaviour of the rope along its embedded length based on these tests.

The developed bond model describes bond behaviour as a function of the bond stress-slip relation. This function depends on concrete strength and the rope geometry. The nonlinear material behaviour of the “concrete wire rope” is formulated by its tangent modulus of elasticity. Furthermore a specified secant modulus of the “concrete wire rope“ can be used in case of low stresses. Calculation and analysing of bond behaviour along a defined embedding length by adapted differential equations are possible. The analysing by FEM is getting feasible as well.

1 INTRODUCTION

Up to now the main usage of steel wire ropes is for steel constructions and conveyor systems. The idea was to use the positive features of steel ropes, e.g. high strength and the flexibility, in combination with concrete. Examples of practice are products to reinforce construction joints similar rebending connections. A systematic scientific examination (Avak et al. [2]) could find the most suitable type of rope regarding bond in concrete. The one-layered round strand rope according to 6 x 19 Standard with metallic core showed the most favourable results in the series of tests. This type of wire rope had been used in all further investigations and modeling (Wille [7], [8]).

The general application of not prestressed steel ropes as statically designed reinforcement requires precise knowledge on the bond behaviour. A basic knowledge on material laws, influence parameters and the extent of the bond is necessary. Extensive experimental investigations were conducted to that. The following contribution reports about the experimental tests and modeling of the bond and strain behaviour of the examined round strand ropes in concrete.

2 EXPERIMENTAL INVESTIGATIONS

2.1 Pull-out tests

First of all pull-out tests were conducted appraising the rigid and soft bond connecting steel ropes and concrete (Avak et al. [3]). In order to examine the influence of concrete strength, different concrete mixtures were used. A reinforcing steel bar was included in all test series for the comparative judgment of bond capacity of wire ropes.

In accordance with figure 1 the setup of test prism was mainly based on the RILEM-pull-out specimen (RILEM [5]). Due to some specific characteristics, like low bending stiffness of rope body, torque and nonlinear property of material modifications in specimen construction were realized.

Tensile force causes torsion in the rope body as a result of the torque of strands. Because of the fixed support of the crack edges in the area of cracks in real members, this rotation is not possible. To consider this effect a piston-slide construction (see figure 1) was fixed on the loaded and the unloaded face of the specimen.

The displacements were measured on the loaded, as well as on the unloaded face of the specimen. This measurement was realized with a telescope mechanism composed of two copper tubes, gliding into each other. One side of the inner copper tubes was squeezed on the round strand rope. Hereby it was possible to grip the relative slip from the end of the bond length and to transmit it to the outside of the specimen. While the ropes were pulled out, the displacements were measured at the loaded and the unloaded face of the specimen. The measurement was carried out by three inductive displacement transducers arranged in an angle of 120° on each face of the specimen.

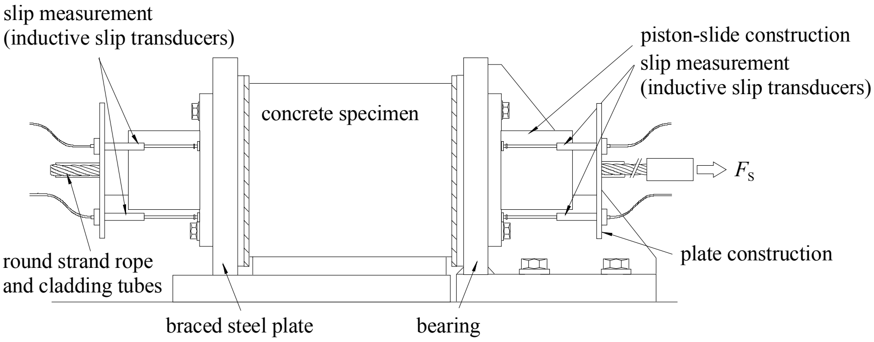
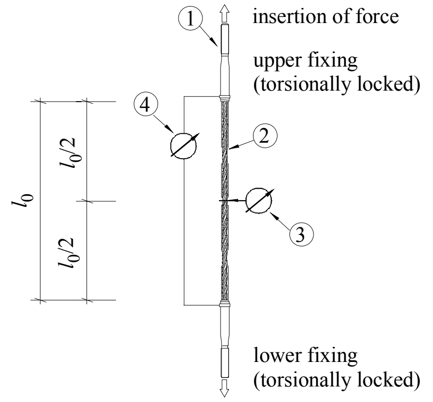


Figure 1: Setup of pull-out test

2.2 Strain tests

The complete description of bond along a defined embedding length needs knowledge on the strain behaviour of the steel wire ropes in concrete additionally. A concrete penetrated steel wire rope (shortly: concrete steel wire rope) with changed material properties arises from embedding of a free rope in concrete. In particular the strain behaviour depends on the filling of the steel wire rope with concrete during concreting and compacting. Concerning this stress-strain relation and transverse contraction of the concrete steel wire ropes were quantified by strain tests (Wille [8]). These tests were carried out by the experimental setup represented in figure 2. Three inductive displacement transducers registered the longitudinal strains, being applied at a plate construction attached to the thread terminals. The measurement of the transverse contraction was realized by two inductive displacement transducers which were applied to the middle of the rope length l_0.



Position	Description
①	thread terminal
②	concrete wire rope
③	transverse strain measurement (2 inductive displacement transducer)
④	longitudinal strain measurement (3 inductive displacement transducer)

Figure 2: Setup of strain test

3 MODELING

3.1 Calculation of bond stresses

The bond stresses of the ropes are calculated using a substitute bar (see figure 3) with a substitute diameter d_e that supposes a rope body penetrated completely with cement paste. This diameter of the fully penetrated remaining cross section is determined by subtracting the external spandrel area A_r from the circle area that is calculated with nominal diameter d_s. The substitute diameter d_e is calculated using the following equation:

$$d_e = \sqrt{{d_s}^2 - \frac{4 \cdot A_r}{\pi}} \tag{1}$$

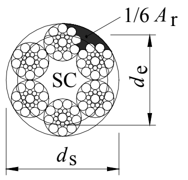


Figure 3: Definition substitute bar

The bond stress τ_b is calculated by dividing the tensile rope force F_S with bond perimeter u_b and the bond length l_b in accordance with eqn (2). The assumption of an equable spreaded (i.e. constant) bond stress over the embedding length seems to be suitable because of the examined short bond length l_b.

$$\tau_b = \frac{F_S}{u_b \cdot l_b} \tag{2}$$

The bond perimeter u_b of the round strand rope is determined by using the substitute circle section (substitute bar, see figure 3) related to eqn (3).

$$u_b = d_e \cdot \pi \tag{3}$$

3.2 Calculation of the related rib area

The value of the related rib area f_R is defined for inclusion of the rope geometry. The idea is a rib formed by wires and strands at the outer surface of a rope.

$$f_R = \frac{A_r}{A_s} = \frac{A_r}{\pi \cdot d_s \cdot l_s} \tag{4}$$

The related rib area f_R can calculate in accordance with eqn (14) about the relation of the entire spandrel area A_r (see figure 3) to the body surface of the rope A_s considering the real rope diameter d_s within a length of lay l_s.

3.3 Bond modeling

A bond stress-displacement function was derived from the results of the pull-out tests for numerical description of the bond behaviour. The character of the carried out tests approves the derivation of a global bond law with a middle bond stress-displacement relationship.

The description of the local bond stresses $\tau_b(x)$ of the concrete steel wire ropes is realized by a nonlinear potency approach considering the influence parameters: local displacements $s(x)$, concrete compressive strength f_c and the value of the related rib area f_R in accordance with eqn (5).

$$\tau_b(x) = 1{,}55 \cdot 10^7 \cdot s(x)^{0{,}15} \cdot f_c^{0{,}75} \cdot f_R^{3{,}5} \tag{5}$$

The own investigations of bond behaviour of reinforcing steel bars (Wille [6]) result a bond law according to eqn (6).

$$\tau_b(x) = 0{,}86 \cdot s(x)^{0{,}32} \cdot f_c^{0{,}98} \tag{6}$$

Figure 4 shows the model law for the bond behaviour of the round strand ropes at the example of the series of tests with a rope diameter 8 mm. The principal suitability of the approach is shown in the diagram. Comparison of ropes and reinforcing steel bars shows by far smaller bond stresses of the wire rope combined with a more rapid flattening of the bond stress-displacement curve.

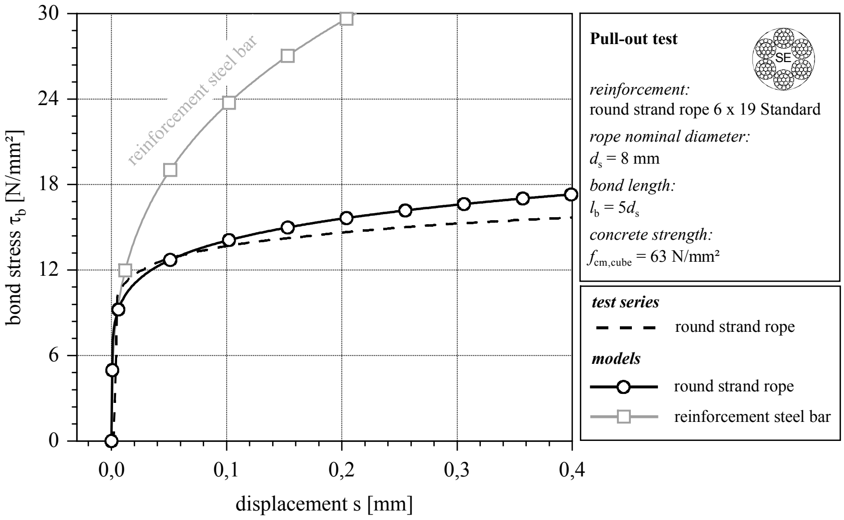


Figure 4: Comparison of experimental and model results

3.4 Strain behaviour of the "concrete wire rope"

Related to modeling of strain behaviour of the concrete wire ropes two contemplations to the rope modulus of elasticity are made fundamentally (Feyrer [4], Wille [6]).

The evaluation of the secant modulus was manifested between a lower ($\sigma_S = 0$) and an upper ($\sigma_S = 800$ N/mm²) rope tensile stress in the first approach. Hereby the declaration of a practice-oriented value for the consideration of the strain behaviour of concrete steel wire ropes is possible.

The second approach is defined by a tangent rope modulus of elasticity. This allows describing the rope modulus of elasticity over the entire range of loads. Furthermore a more precise evaluation of the strains between two rope stresses is possible. Detailed calculation are not introduced at this place. Further information can be taken from (Wille [6]).

The carried out analysis of regression with test data led to eqn (7) as a definition for the secant modulus of elasticity of the concrete steel wire ropes considering the examined influence parameters. The rope diameter has dimension [mm] in eqn (7), concrete compressive strength f_c [N/mm²], secant rope modulus of elasticity $E_{s,BDS}$ [N/mm²].

$$E_{s,BDS} = 82700 \cdot \left[1 + \left(0,06 \cdot d_s^{\,0,38} \cdot f_c^{\,0,23}\right)\right] \tag{7}$$

4 CONCLUSIONS

The general application of not prestressed steel ropes as statically designed reinforcement requires precise knowledge on the bond behaviour. A basic knowledge on material laws, influence parameters and the extent of the bond is necessary. Extensive experimental investigations were conducted to that.

Global bond behaviour was studied by pull-out tests. The tests analysed the influences of concrete strength, rope geometry and bond length. To account for the special properties of the ropes (like torque of strands) the usual setup was modified thereby. A relation between bond stress and slip was used to analyse the results. A non-linear potency function which consists of a bond stress-slip relation was derived. This one allows describing the bond between steel wire rope and concrete.

Strain behaviour within the embedding length and/or between two cracks was up to now unknown. Therefore extensive strain tests were carried out. Experimental investigations registered the laws in the composite material concrete steel wire rope. Dependences and influences of different limiting conditions and parameters could be presented. an equation is proposed for the modulus of elasticity of the concrete steel wire ropes derived from experimental results. The function considers the variables of rope diameter and concrete strength. It could be verified, that larger rope diameter and higher concrete strength lead to higher modulus of elasticity of the concrete steel wire ropes.

5 REFERENCES

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