Influence of concrete thermal degradation on anchorage zones of externally-bonded reinforcement

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ABSTRACT: This paper is identification of problem behaviour of anchorage of externally bonded reinforcement on concrete constructions. The tests were realized with FRP strips. The main problem was to determine the influence of thermal degradation of concrete for the load capacity of anchorage zone. This influence was evoked by several different (0, 50, 100 and 200) cycles of freezing of concrete-FRP bond. Tests were performed both as the short-terms and long-terms ones. All tests were made for different anchorage length. The test results were compared with values obtained from analysis of anchorage zones behaviour in nonlinear FEM method. New analytical relationship was also developed to define the behaviour between strip and concrete along the anchorage zone. Finally, control calculations were carried out according two different standards (ACI and Czech standards) and compared with the previous results.

1 INTRODUCTION

Strengthening methods using externally bonded reinforcement are well explored and often used in the Czech Republic and abroad. Within the context of using new technology and new materials it is necessary to adapt the methods of design and application to native conditions in the Czech Republic. Thereby it is possible to restrict damages caused by lack of information about proper design and proper working process.

For that purpose it was necessary to perform series of the short-terms and long-terms tests in local climatic conditions and with using accessible common materials. One range of the research task was focused on anchorage zones of externally bonded reinforcement. Research work was concentrated on following influences:

- influence of anchorage length of externally bonded strip on carrying capacity,
- influence of thermal degradation of bond on deformation (strain) of anchorage zone and its carrying capacity,
- influence of long-term load impact on thermally degraded bond between external reinforcement and concrete

2 SHORT-TERMS TESTS

The short-terms experiments serve as a base for a design of strengthening. The short-term experiments involved a series of the tests on a concrete specimen, on which distinct lengths of CFRP glued reinforcement were applied. These specimens demonstrate the behaviour of the reinforcing element under tension and adhesion between individual layers in the reinforcement area.

Anchorage blocks of dimension 150x150x600 mm were prepared from defined standard concrete quality (C20/25 according to EC2). The CFRP strips of cross-sectional dimension 50x1.2 mm and Young's modulus 155 GPa were bonded to the prepared surfaces of different anchorage lengths - 150, 225 and 300 mm (see Fig. 1a). The aim of the tests was to determine the ultimate axial forces, which could be anchored by different anchorage lengths and by different stress acting on the anchoring area. Tested alternatives are shown in Figure 1b (anchoring without stirrup – i.e. without the cross force acting on the anchorage area), Figure 1c (anchoring with stirrups without perpendicular prestressing on the contact area between the strip and concrete) and Figure 1d (anchoring with prestressed stirrups).

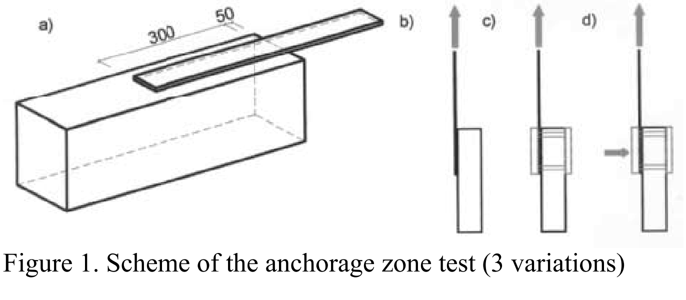


Figure 1. Scheme of the anchorage zone test (3 variations)

There were three different anchorage lengths (represented with three test specimens with the same anchorage length) in each test alternative. In variation described in Figure 1d there were twice as much specimens and they were tested with different prestressing force.

During the tests it was possible to trace development of stress along the anchorage areas for individual load phases and activation of the anchorage zone. Also the weakest point of this bond system was determined – the failure happened under the bonded strip in surface layer of concrete as can be seen in Figure 2. So the limitation factor of load carrying capacity is the concrete or more precisely the tension capacity of concrete.

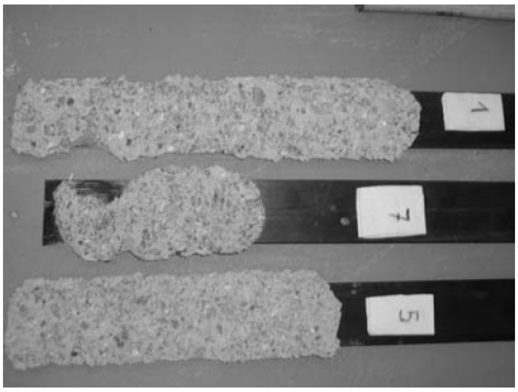


Figure 2. Ripped off strips with the residue thin concrete layer

The test showed that at the higher level of loading a crack generated in the surface layer of concrete and it shifted active section of anchorage zone. This crack distributed quickly itself and soon after its origin the strip ripped off. Maximal load force could be increased by applying the prestressing force along the anchorage zone. This positive influence is clearly shown in Figure 3.

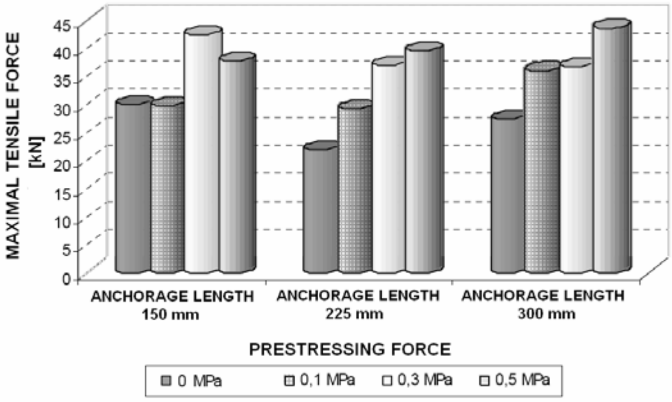


Figure 3. Influence of the prestressing force on carrying capacity of the anchorage zone

In terms of theoretical interpretation, for such test specimens it is possible to derive basic differential equations (Brosens K. & Van Gemert D. 1999) for normal and shear stresses in concrete and adhesive, normal stress in a strengthening member (CFRP strip) for several boundary conditions. The elastic behaviour of all materials used (concrete, rebar, adhesive and CFRP strips), full co-operation between bonded strip and concrete and uniformly distributed stresses and strains over the entire width of a cross section of the anchorage area was assumed. The derived equations for normal stress in the CFRP strip $\sigma_p(x)$ and the shear stress $t_p(x)$ in a direction of axis x in the adhesive and the normal stress $\sigma_n(x)$ in the perpendicular direction to the surface of a concrete specimen under glued strip is given by

$$\sigma_p\left(x\right) = C_1 e^{Ax} + C_2 e^{-Ax} - \frac{A_c B_2}{A^2}\left(l - x + a\right) \qquad (1),$$

$$\tau_p\left(x\right) = t_p\left[C_1 A e^{Ax} - C_2 A e^{-Ax} - \frac{A_c B_2}{A^2}\right] \qquad (2),$$

$$\sigma_n\left(x\right) = e^{-\beta x}\left[D_1 \cos\left(\beta x\right) + D_2 \sin\left(\beta x\right)\right] \qquad (3),$$

where

$$A^2 = A_p + A_c B_1 \quad ; \quad A_p = \frac{G_a}{t_a t_p E_p} \quad ; \quad A_c = \frac{G_a}{t_a t_p E_c} \quad ;$$

$$B_1 = -\frac{b_p t_p}{A_{tr}}\left(\frac{z_{ctr}^2}{i_{tr}^2} - 1\right) \; ; \; B_2 = F\,\frac{z_{ctr}^2}{J_{tr}}\,\frac{1}{l + a + b} \; ;$$

t_a is the thickness of the adhesive; t_p is the thickness of the CFRP plate; E_p is the Young's modulus of the CFRP strip; E_c is the Young's modulus of concrete; G_a is the shear modulus of the adhesive.

Using the appropriate boundary conditions the constants C_1 , C_2 , D_1 and D_2 can be identified.

In order to control the comparison of experimentally obtained results and results of the solutions of analytical equations, physically non-linear FEM modelling based on the fracture mechanic model of concrete was used. The behaviour of the other materials (adhesive, CFRP strip) was considered as linear. The calculations were made by software ATENA while deterministic material characteristics for concrete, adhesive and strip were supposed.

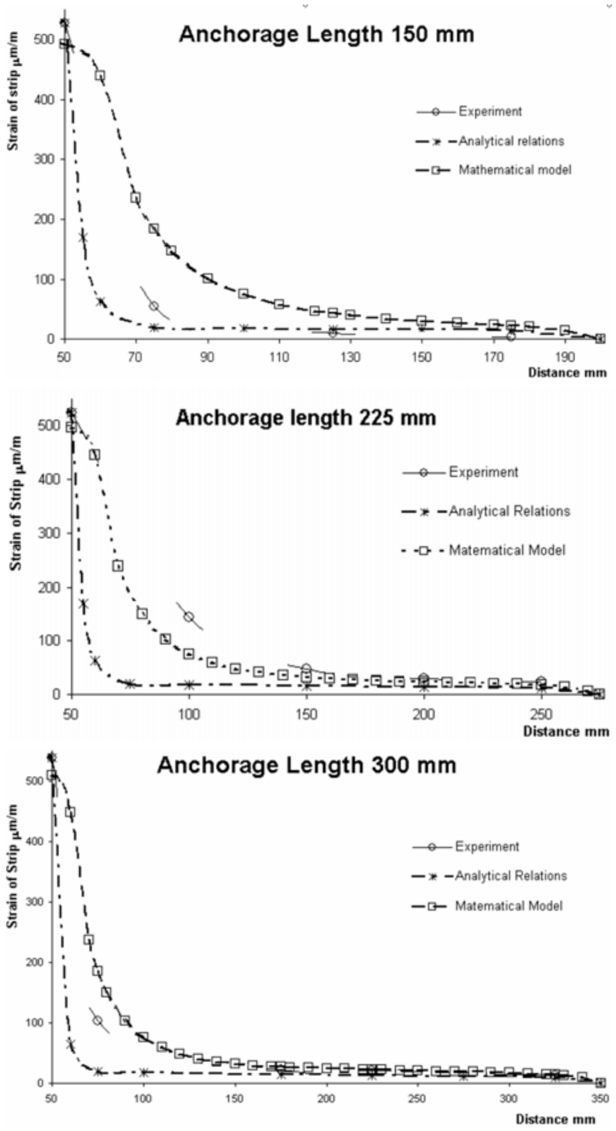
The physical-mechanical properties of both strip and glue were assumed according to data provided by producer (they were not tested).

Table 1. Material properties for strip and glue used in calculations

	E [MPa]	μ	Thickness [mm]
carbon strip	155,000	0.3	1.2
glue	8000	0.3	1.4

Concrete material parameters used in calculations were taken from the control tests of concrete samples.

The results of experimental, analytical and numerical solution of the strain along the glued length are shown in Figure 4.



a)
b)
c)

Figure 4. Comparison of the longitudinal strain along the glued length a) 150 mm b) 225 mm c) 300 mm

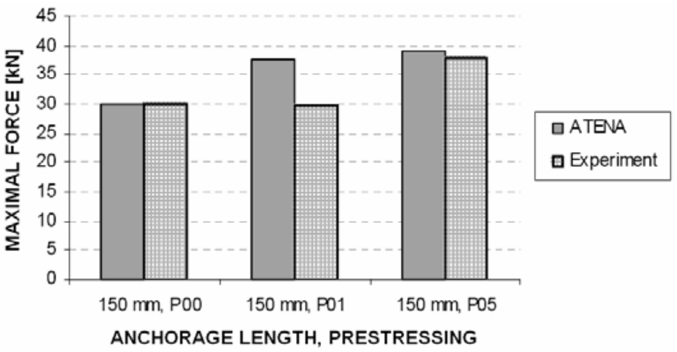


Figure 5. Comparison of the maximal acting force – anchorage length 150 mm, prestressing 0.0 MPa (P00), 0.1 MPa (P01) and 0.5 MPa (P05)

The positive effect of perpendicular prestressing acting on the anchorage zone was proved also in numerical solution as the maximal force increased significantly (nearly 30% of initial value). Comparison of results from experiment and numerical model are in Figure 5.

To test the influence of deterioration of concrete caused by the temperature changes, the same specimens with glued lengths 225 and 300 mm were used. The test specimens with the glued strips were frosted and re-frosted in a water solution. The temperature change moved between -15°C and 15°C, the velocity of the temperature cycle was ± 2°C/hour and the maximal and minimal temperature was hold for 4 hours. The specimens were loaded with 0, 50 and 100 temperature cycles, respectively. Each set contained three test specimens.

The results of short-term tests are shown in Table 2. The influence of freezing cycles on the glued connection behaviour is significant. Also by growing number of the freezing cycles the deformation of the strip free end grows (Fig. 6) and the ultimate limit force in the strip decreases.

Table 2. Maximal load forces for different anchorage lengths and different level of thermal degradation

	Anchorage length 225 mm		
	0 cycles	50 cycles	100 cycles
average value	**29.428**	**25.553**	**27.081**
standard deviation	4.68	1.06	1.03
	Anchorage length 300 mm		
average value	*	**36.246**	**29.748**
standard deviation		4.48	0.51

* Values could not be obtained due to imperfect glue

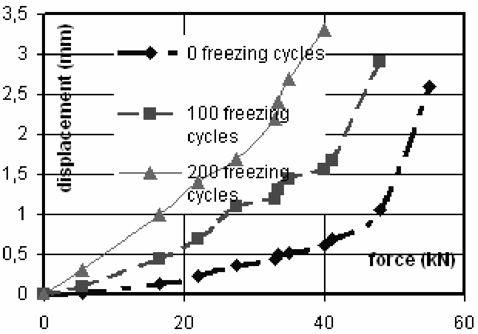


Figure 6. Influence of number of the freezing cycles on dependence of the strip free end displacement and the tension force

The failure of the bond system occurred in the same manner as in the short-terms tests, i.e. crack developed in the concrete near surface with bonded strip, quickly extended and caused delamination of the strip. The tensile capacity of the concrete remained the limitation point of this bond system.

The influence of number of freezing cycles to limit load force can be approximately defined by the diagram - Figure 7 - for glued anchorage of strip (50/1.2 mm and Young's modulus 155 GPa) on concrete C20/25. The calculation form is

$$\frac{F_{sc}}{F_{scm}} = \frac{k\eta - \eta^2}{1 + (k-2)\eta} \tag{4}$$

where $F_{sc} = F_{sc}(n)$ is force in strip (depended on n); $\eta = u_c/u_{c1}$; $u_{c1} = u_{c1}(n)$ is the displacement of the free strip end at peak anchoring force $F_{scm} = F_{scm}(n)$; $k = E_{scm} \times |u_{c1}| / F_{scm}$ and values $u_{c1}(n)$, $F_{scm}(n)$ are obtained from experiments – Figure 7.

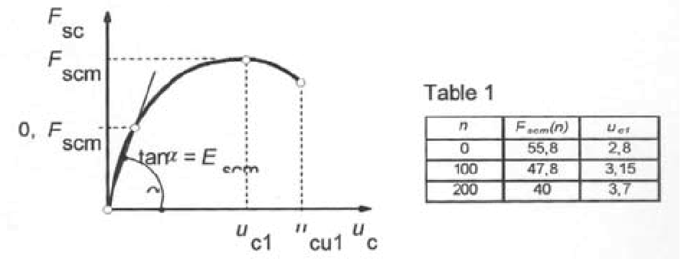


Table 1

n	$F_{scm}(n)$	u_{c1}
0	55,8	2,8
100	47,8	3,15
200	40	3,7

Figure 7. Schematic representation of the expression (4) showing the progress of thermal degradation influence of glued connection

The expression (4) was verified in terms of set of others 6 test specimens. However the use for the long-terms load acting needs additional tests and verification.

3 LONG-TERMS TESTS

The long-terms tests were performed with specimens loaded with 0 (reference), 100 and 200 freezing cycles described above. All specimens (total lay-out of test specimens see in Table 3) were consequently put into steel construction that allowed to develope permanent load to reinforcement. The anchorage zones length were 225 mm and 300 mm for each set of freezing cycles.

Table 3. Number of test specimens during the long-term test

Anchoring length	Number of test specimens cycles		
	0 cycles	100 cycles	200 cycles
225 mm	3	3	3
300 mm	3	3	3

All test specimens were made at time t = 0 days. At time t = 28 days the strips were bonded to the concrete blocks. In the same day part of the specimens was stored to the freezing machine and the exposure of the freezing cycles begun. Unexposed specimens were stored separately in standard conditions but they were not loaded. The loading force was applied after all specimens went through prescribed freezing cycles. All 18 specimens were loaded in the same day.

Tension force was put into reinforcement via pre-stressed spring. Initial force value was 5 kN (i.e. 20% of total load carrying capacity of anchorage zone) and it was slowly increased to present 6.3 kN.

During the experiment strain along the anchorage zone was monitored via strain gauges (same configuration as in the short-terms tests). The acting load force was monitored indirectly by measuring the strain in free end of reinforcement.

Response of seven specimens was measured in 10 minutes intervals by a measuring central. This central recorded also the temperature of surroundings and thus it was possible to eliminate the influences of temperature changes (not-loaded compensation reinforcement elements were measured too). The rest of loaded specimens were measured in the longer time intervals.

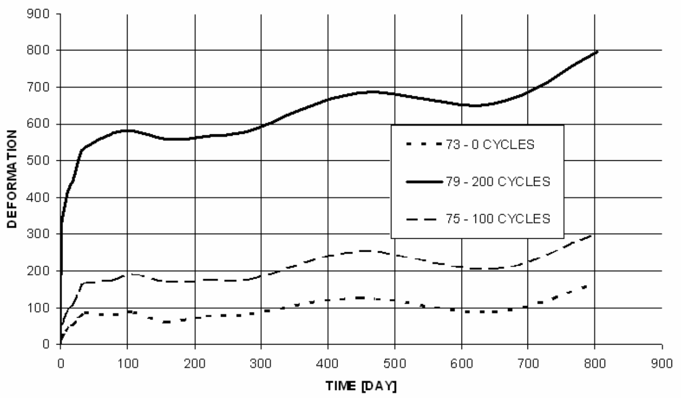


Figure 8. Deformation progress for anchoring length 225 mm

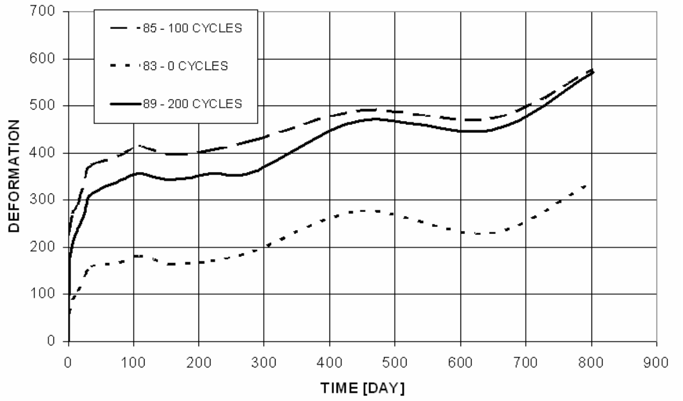


Figure 9. Deformation progress for anchoring length 300 mm

4 MATHEMATICAL MODELLING

Model of anchorage zone was created in non-linear FEM solver ATENA based on fracture energy of quasi-brittle materials.

Material models for reinforcement and bond material were presumed as elastic with characteristics shown in Table 1 and in addition $\alpha_p = 1.2\times10^{-5}$ (for CFRP reinforcement), $\alpha_p = 9\times10^{-5}$ (for bond). Some material characteristics for concrete were taken from performed tests (tensile and compression strength) and the rest values were derived through relations in ČSN 73 0038. Concrete material was modelled as non-linear.

Standard Newton-Rhapson method was used for problem solving. FEM mesh was created as quadratic with refinement under problematic zone (Fig. 10). Boundary conditions were the same as in experiment and also positions of monitoring points corresponded with real strain gauges.

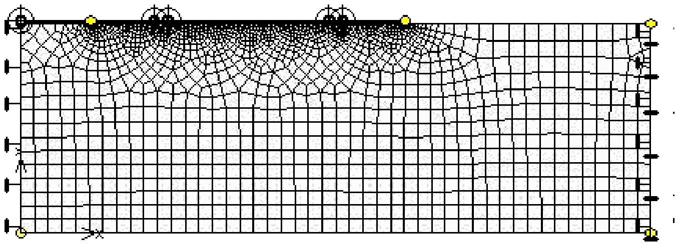


Figure 10. FEM mesh used in calculation

In the first step all input data were more precisely identified during comparison of real experiment outputs and numerical solution of the short-terms test of carrying capacity.

Lately two different numerical models were used for creep solution – model based on standard ČSN 73 1201 and model B3 (developed by Bazant and Al Manaseer). The results obtained from mathematical model corresponded well with reality. Thus it is possible to use these creep material models for further solutions and construction calculations. This model is also possible to use for verification of developed analytical relations.

Creep rupture of the CFRP strip was not considered in the numerical model. The stress level in bonded strip during the experiment was very low and the ratio of stress level at creep rupture was determined (Yamaguchi 1997) to be 0.91 which value was not reached during test. Also the modulus of elasticity is typically unaffected by environmental conditions (in this case several numbers of freeze-thaw cycles) hence the material properties of CFRP strip were not considered as time-dependent.

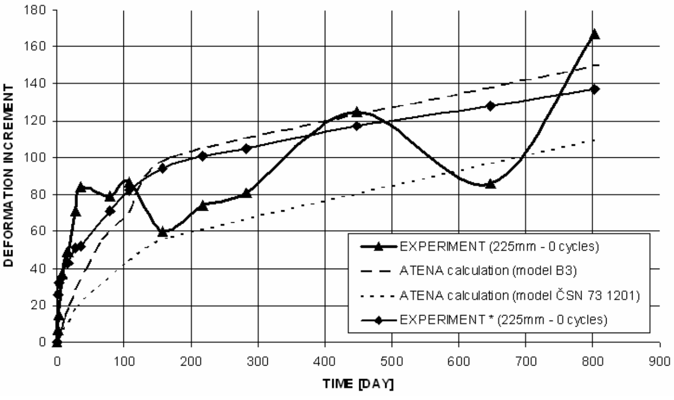


Figure 11. Increment of deformation in anchorage zone (comparison between numerical analysis and two real test specimens).
* Values are re-calculated to eliminate deformations caused by temperature changes.

The numerical model (using B3 material creep model) shows good correspondence with the real long-term test results obtained on thermally non-degraded specimens.

In the next step it will be necessary to find material model including thermal degradation of concrete. Such simplification (i.e. neglected time-depending changes of material characteristics of CFRP) is possible because of relatively stable material characteristics of CFRP strips unaffected by thermal degradation.

5 CONCLUSIONS

The comparison of the theoretical, measured and numerical non-linear FEM analysis results of stress and strain at the anchorage areas demonstrates good accordance at the linear area of behaviour. The theoretically derived design equations can be used for anchorage of non-prestressed and prestressed CFRP strips.

From the analytical and numerical analysis it is evident, that the anchoring length of CFRP strips on concrete C20/25 is about 365 mm. By increasing the anchoring length the maximum tension force in CFRP strip does not grow.

The failure of anchorage area (of glued contact) starts in concrete – from the beginning of the strip. The main reason for the failure initiation is the normal stress acting perpendicularly to CFRP strip axis.

From the long-terms tests carried out until now it can be stated that there was an evident influence of the number of freezing cycles in the growth of strain in anchorage zone while the permanent constant load. The shorter the anchorage zones the more severe influence. This can be partially restricted by the longer anchorage zone.

While creating numerical model of the long-term loading on thermal degraded structure it is possible to use the simplification and to use only simple material models for externally bond reinforcement (if CFRP materials are used – other materials may show more significant time-depended material degradation). It is enough to consider only concrete degradation as it is the limit factor for carrying capacity of anchorage zone.

6 ACKNOWLEDGEMENT

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