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Evaluating the bond stress relationship of externally bonded CFRP-strips at the intermediate crack element

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ABSTRACT: When reinforced concrete is strengthened by using externally bonded CFRP strips it is not sufficient to perform checks just for the end anchorages. The bond forces must be transferred where the load is applied. These bond forces may be transferred by the elements in between flexural cracks which are mainly influenced by the bond behavior of the internal and external reinforcing. Therefore the models which were derived from end anchorage tests must be expanded to include other effects as well.

These models were first described theoretically by the differential equation of bond and a bilinear bond stress slippage relationship. To evaluate this theoretically derived relationship numerous experiments on the intermediate crack elements where conducted.

In this paper, an evaluation of these experiments in two different ways is shown. The one evaluation is carried out only on the fracture force, the other analysis also takes the slippage occurred in the intermediate crack element tests into account.

With both evaluations it can be shown, that besides the previously scheduled bilinear bond approach additional friction effects between the already decoupled fracture surfaces of the bonded strips occur.

1 INTRODUCTION

For concrete structures, strengthening with externally bonded CFRP-strips presents an established method which allows the subsequent increase or restitution of the load-bearing capacity as well as an improvement in serviceability.

Besides the well known failure modes of the conventional reinforced concrete there are some special failure modes, which can occur on reinforced concrete beams strengthened with CFRP-strips. Numerous full scale tests carried out in recent decades had shown, that usually the bond failure on structural elements with externally bonded reinforcement will prevail and particular bond approaches are needed for this failure.

In conventional reinforced concrete usually bond checks are done by end anchorage verifications, which are based on bond values from pullout tests. If one introduces such verifications in similar form to structural elements with externally bonded reinforcement, the full tensile strength of the CFRP-strip cannot be anchored, because after a specific length, the bond forces cannot be increased anymore (See also Figure 1). However, almost all full scale tests have shown that much higher forces in the externally bonded reinforcement are reached at the place of the maximum bending moment, as it would be possible looking only at the end anchorage.

On CFRP strips with their high tensile strength, the sole consideration of the end anchorage would be not cost-effectively. Thus the bond forces of the CFRP-strips must be transferred at the point where the forces occur. For this reason two areas are distinguished for bond verifications, the end anchorage zone and the rest of the structural element. At the end anchorage zone the forces of the CFRP-strip must be anchored, which occur at the outermost bending crack. The bearable bond forces at the end anchorage zone can be determined by so-called idealized end anchorage tests, in which the externally bonded reinforcement will be pulled off in the longitudinal direction.

In the remaining area of the structural element, the bond force can be transferred by elements, which are separated by bending cracks, the so-called intermediate crack element (ICE). On such an intermediate crack element there is always a basic force in the strip at the lower stressed crack and at the higher stressed crack there is this basic force plus an additional force. This additional force must be transferred by bond to the structural element.

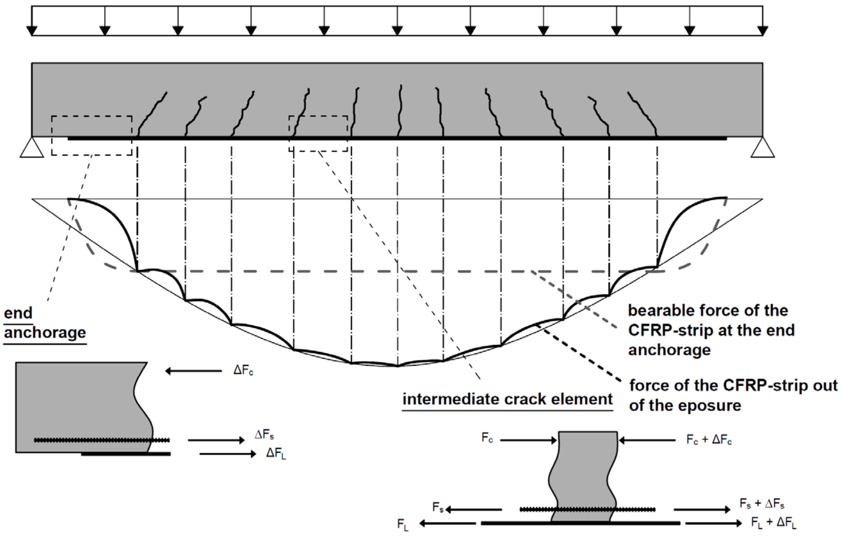


Figure 1. Principle of the bond force transfer of externally bonded CFRP-strips

2 THEORETICAL BASIS

The bond of externally bonded reinforcement is currently treated by the differential equation of bond-slip as shown in equation (1). It is described by the strip's slippage s_L , the thickness t_L and elastic modulus E_L as well as the bond stress/slippage relationship $\tau(s_L)$.

$$s_L'' - \frac{1}{E_L \cdot t_L} \cdot \tau(s_L) = 0 \tag{1}$$

A serviceable approximation of the bond stress/slippage relationship for the idealized end anchorage experiment is the bilinear bond approach as shown in figure 2 a. It consists of an initial elastic ascending curve and a plastic descending curve. The values of the parameters depend on the strengthening system and are determined on end anchorage tests. For externally bonded CFRP strips the values were determined by Zehetmaier (2004) and are listed in Table 1 (Where

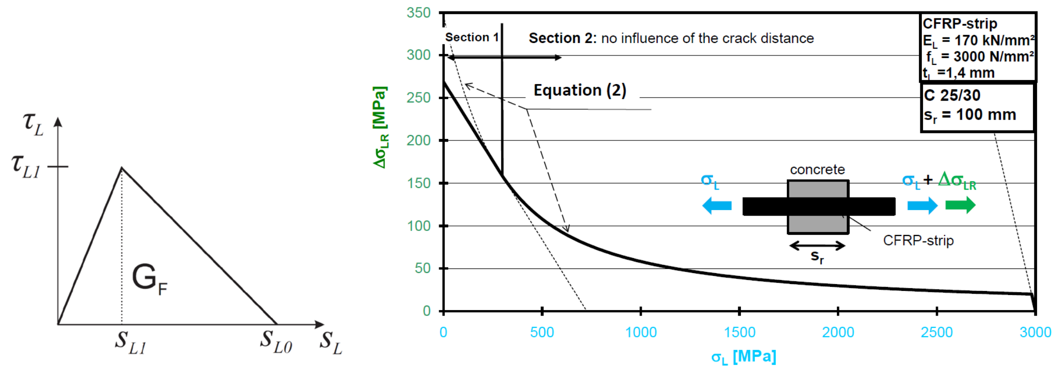
τ_{L1} is the maximum bond stress, s_{L0} is the maximum slippage, s_{L1} is the elastic slippage, f_{cm} is the mean cylindrical concrete compression strength according to EN 12390-3 and $f_{ctm,surf}$ is the mean tensile surface strength according to EN 1542).

Table 1. Values of the bilinear bond approach for externally bonded CFRP-strips

	τ_{L1}	s_{L0}	s_{L1}
	N/mm²	mm	mm
Mean Value	$0.527 \cdot \sqrt{f_{cm} \cdot f_{ctm,surf}}$	$2.12 \cdot 10^{-1}$	$\approx 2 \cdot 10^{-2}$
Design Value	$0.366 \cdot \sqrt{f_{cm} \cdot f_{ctm,surf}}$	$2.01 \cdot 10^{-1}$	-

These values also cover the reference end anchorage tests of Zilch et al. (2010) in the average well, which were carried out with the same material combination as the tests on the intermediate crack element.

For an intermediate crack element as seen in figure 1, Niedermeier (2001) solves the differential equation of the bond slip (Equation (1)) using the bilinear bond approach according to figure 2 (a) for boundary values as they would apply for idealized elements between cracks. The result is a relationship at the intermediate crack element that can be used to calculate the additional resisting stress for the strip in relationship to the base stress.



(a) (b)

Figure 2. (a) Bilinear bond stress slippage relationship; (b) Relationship at the intermediate crack element between basic stress and bearable additional stress according to Niedermeier (2001)

The relationship, which is shown in figure 2 (b), is two-tiered. The first section has a lower base stress which is influenced by the length of the crack element. In the second section, however, the bond stress resistance is no longer affected by the length of the crack. Through linearization of the bilinear approach Niedermeier (2001) obtains the additional resisting stress in the strip $\Delta\sigma_L$ for section 2 (Equation (2)) which only depends on the bond fracture energy G_F and the strip characteristics.

$$\Delta\sigma_{L,BL,R} = \sqrt{\frac{2 \cdot G_F \cdot E_L}{t_L} + \sigma_L^2} - \sigma_L \tag{2}$$

For conventional CFRP strips and typical crack distances the crack distance is negligible, so it is only necessary to look at part 2 (Equation (2)). Additionally the tensile strength of the CFRP strip limits the strip's resisting stress through bonding.

3 EXPERIMENTAL INVESTIGATIONS

3.1 Test setups

In order to verify the relation on the intermediate crack element empirically, Thorenfeld (2002), Schilde and Seim (2007), Zilch et al. (2010) and Ellinger (2010) performed tests on an idealized intermediate crack element with a schematic set-up as shown in figure 3. In this experiment, CFRP strips were applied to both sides of a concrete specimen. On either side differing forces were applied until the CFRP strip detaches completely. In the different experimental investigations other concrete mixtures, geometries and CFRP-strips were used.

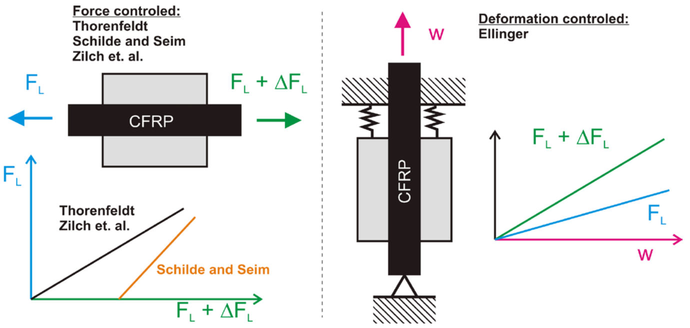
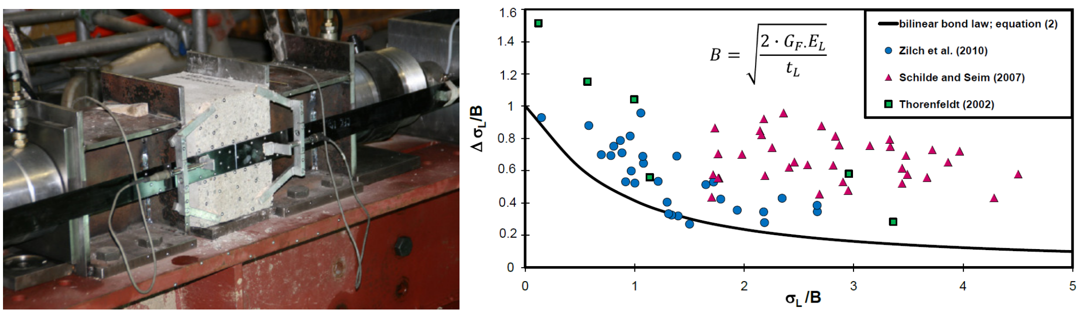


Figure 3. Different test setups for the tests on the idealized intermediate crack element

But the major difference of these investigations is the application of the load as seen in figure 3. In the tests of Thorenfeld (2002), Schilde and Seim (2007) and Zilch et al. (2010) the load was applied force controlled. This can be done for example with two separately controlled hydraulic jacks as seen in figure 4 (a). The tests of Thorenfeld (2002) and Zilch et al. (2010) were controlled so, that the force difference was increasing continuously with the basic force. By contrast in the test of Schilde and Seim (2007) the specimen was first loaded with a constant basic force and then loaded only with the force difference until the failure occurred. On the test series of Ellinger (2010) the load was applied deformation controlled with a standard testing machine. The force difference was applied with a disc spring.

3.2 Results

For all test series a significantly higher level was achieved than the simplified theoretical approach would predict. The test results of the single tests are plotted together with the simplified theoretical approach in figure 4 (b).



(a) (b)

Figure 4. (a) Photo of the test setup of Zilch et. al. (2010); (b) Results of all intermediate crack element tests

This can be traced to the friction effect between the bond fracture surfaces that form even before the bond completely fails which is not included in the bilinear bond approach. This bond friction results from the jagged grain of the rough fracture surfaces which normally run through the concrete surface layer and can reach a maximum depth corresponding to the maximum grain diameter of the concrete.

3.3 General evaluation and interpretation

For the evaluation of the tests and hence for the determination of the bond friction stress there are now two possibilities:

1. Numeric solving of the differential equation of bond and the determination of the four parameters of the extended bilinear bond approach by the friction on the strip strains and the slippage of the test. This is done in section 3.5 of this paper (Test evaluation over the slippage).
2. Setting the parameters of the bilinear composite approach to be known and the bond friction stresses can be determined out of the difference between the test results and the previous approach of equation (2). This is done in section 3.4 of this paper (Test evaluation over the fracture force).

3.4 Test evaluation over the fracture force

If the bilinear bond stress/slippage relationship is linearized again and then the differential equation of the sway bond for the additional friction bond stresses is solved then the system can be described by adding the different effects.

$$\Delta\sigma_{L,ICE,I,R} = \Delta\sigma_{L,F,R} + \Delta\sigma_{L,BL,R} \tag{3}$$

The additional resisting strip stress due to bond friction at the intermediate crack element can be calculated through multiplication of the bond friction stress with the already uncoupled surface. This already uncoupled surface can be calculated as the difference between crack distance s_r and effective bond length. The effective bond length is composed of the elastic length s_{el} and plastic length s_{pl}.

$$\Delta\sigma_{L,F,R} = \frac{\tau_{LF} \cdot (s_r - s_{el} - s_{pl})}{t_L} \tag{4}$$

To use these equations the bond friction stress τ_{LF} must now be determined from the experiments. This is done by using the parameters of the bilinear bond approach in table 1 and calculating the difference between the experimental results and the recent approach from equation (2). With this difference the bond friction stress can be back calculated with equation (4).

The already debonded length can be calculated by deducting the effective bond length of the intermediate crack element from the crack distance (length of the intermediate crack element). The effective bond length of the intermediate crack element, which decreases by higher base stresses at the ICE can be calculated with equation (5). This equation was founded by Niedermeier (2001) with a linearization of the bilinear bond law.

$$(s_{el} + s_{pl}) = \frac{2 \cdot t_L \cdot E_L}{\tau_{L1}} \cdot \left(\sqrt{\frac{\tau_{L1} \cdot s_{L0}}{t_L \cdot E_L} + \frac{\sigma_L^2}{E_L^2}} - \frac{\sigma_L}{E_L} \right) \tag{5}$$

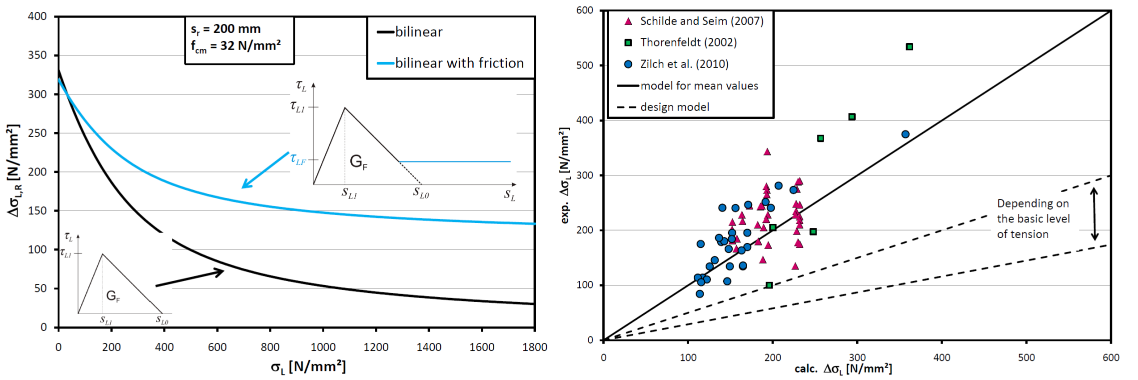
To include the concrete strength in the bond friction stress a power law is used, because by analyzing the outbreak areas of the experiments it was observed that the outbreak in the lower strength concrete was significantly deeper than in the higher strength concrete. It is believed that a deeper outbreak area has a favorable effect on the bond friction which can be described by equation (6).

On the basis of the experiments of Thorenfeld (2002), Schilde and Seim (2007) and Zilch et al. (2010) the following equation for bond friction stress is suggested.

$$\tau_{LF} = k_1 \cdot k_2 \cdot f_{cm}^{-0.89} \tag{6}$$

With: k_1 = 1 for an 8 mm aggregate size and k_1 = 1.4 for an 16 mm aggregate size; k_2 = 17.5 for average values and k_2 = 10.8 for design values

In figure 5, the experiments on the idealized intermediate crack element and the design model are compared. In this diagram, the characteristic value cannot clearly be specified as it depends both on the bond fracture energy G_F of the bilinear approach according to equation (2) and on the bond friction from equation (6). Because the bilinear bond energy and the bond friction depend on the stress level, which are always in a different ration, only a lower and an upper value can be provided here.



(a) (b)

Figure 5. (a) Bilinear bond approach extended with bond friction; (b) comparison of the test values and the calculated values for the bond friction on the idealized intermediate crack element

3.5 Test evaluation over the slippage

In Ellinger (2010) the tests were recalculated by using a numerical simulation. Here the bond between strip and concrete was represented by nonlinear springs. For this method many sections in the bonded length with an appropriate size were defined and described by a spring. In this way one can succeed to solve the bond relationship for high-order approaches. Here the springs were given the bond stress slippage -relationship and multiplied by the surface of an element. The tests on the intermediate crack element were entered with the spring model in the finite element program MSC Marc (2007). Here the load was applied in about 1500 time steps. Both the basic force and the force difference were increased continuously per each time step, as it was the case in the experiments.

To verify the modeling and for illustration here an example of a 200 mm long intermediate crack element with a force difference of 20 percent between both cracks is calculated for the bilinear approach with and without friction and shown in Figure 6. In Figure 6 (a) at the top the forces and the displacements of the strips are shown, which result from the calculation on the intermediate crack element without friction. Below there are shown the bond stresses along the length, which occur at selected load levels of the top image. The Figure 6 (b) illustrates an equal calculation, which takes the friction into account.

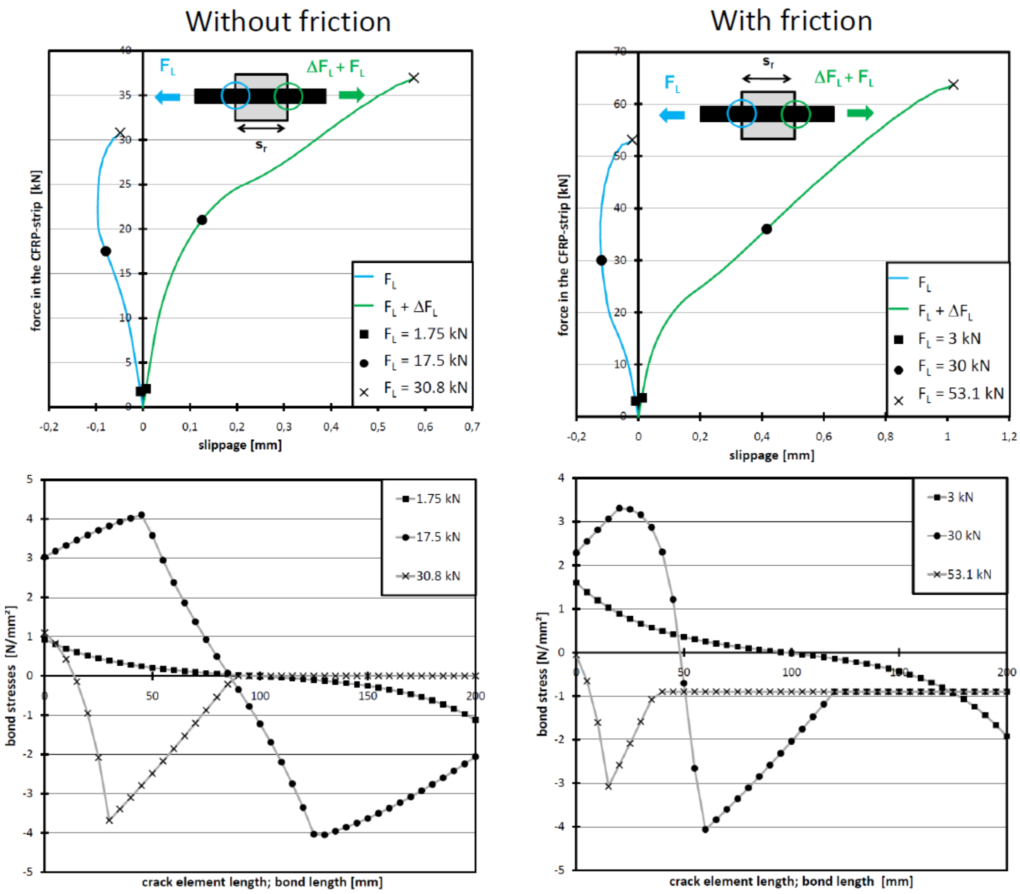
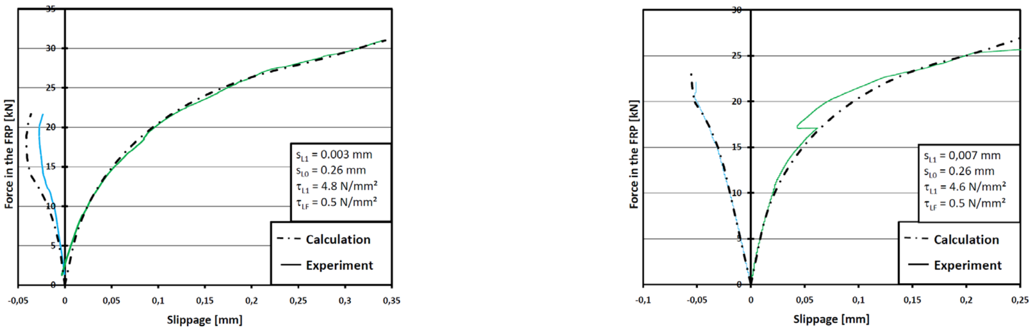


Figure 6. Calculated force- slippage curve and corresponding bond stresses for the bilinear approach and the extended approach for a C20/25 according to EN 206-1

From Figure 6 it can be seen that the approach with bond friction brings a significant increase in the total bearable force difference compared to the approach without friction for small force differences. This becomes even clearer when looking at the bond stress of the last load steps. At the approach with friction there exists a plateau of 0.9 N/mm², from which it can be seen that the area under the curve is significantly larger than without friction. Integrating the bond stresses over the area back, we obtain the bearable force difference.

Because of the numerous tests a representation of the recalculation of all tests is passed and only the possibility and the investigation of such a back-calculation is shown exemplary on the test ZRE-200-20-4-3 from Zilch et. al. (2010) and ZRE 1 from Ellinger (2010). In this recalculation the parameters of the bond stress slip relationship (s_{L1}, s_{L0}, τ_{L1}, τ_{LF}) had been varied until a best match between calculated curve and experiment curve was reached. The results of this back calculation are shown in figure 7. It can be seen, that the run of the experimental data can be simulated well, with the focus of the recalculation laying on the higher-loaded crack. The boundary values of the extended bond approach are in the rage of table 1 and equation (6). (Here the values would be s_{L1} = 0.002 mm; s_{L0} = 0.212 mm; τ_{L1} =4.12 N/mm²; τ_{LF}= 0.9 N/mm²). Thus, the maximum bond stress and maximum slip are a little larger, the elastic slip is somewhat smaller than in table 1 and the bond friction is a little bit smaller than in equation (6).



(a) (b)

Figure 7. (a) Back calculated test of Zilch et al. (2010); (b) Back calculated test of Ellinger (2010)

4 CONCLUSION

On a structural element the bond forces must be transferred at a so called intermediate crack elements (ICE). Up to now the approaches for the ICE are based on theoretical considerations, which are build on the bond energy out of end anchorage tests. With the experiments conducted at the intermediate crack element, which were evaluated here in two different ways, it can be shown that in addition to the previously sole considered bilinear bond approach, a bond friction at the intermediate crack element occurs. With this bond friction it is now possible to calculate structural elements in a more realistic way.

5 REFERENCES

Ellinger, M. 2010: Analyse des Reibverbundes geklebter Bewehrung (Analysis of the bond friction of externally bonded reinforcement), Master's Thesis, Technische Universität München, 57 pp. (in German)

EN 12390-3. 2009: Testing hardened concrete - Part 3: Compressive strength of test specimens, European Committee for Standardization, 19 pp.

EN 1542. 1999: Products and systems for the protection and repair of concrete structures - Test methods - Measurement of bond strength by pull-off, European Committee for Standardization, 8 pp.

EN 206-1. 2000: Concrete - Part 1: Specification, performance, production and conformity, European Committee for Standardization, 79 pp.

MSC Software. 2007: Marc® 2007 r1, FEM-Solver

Niedermeier, R. 2001: Zugkraftdeckung bei klebearmierten Bauteilen (Verification of the tensile envelope line for structural elements with externally bonded reinforcement), Ph.D-thesis, Technische Universität München, 230 pp. (in German)

Schilde, K. and Seim, W. 2007: Experimental and numerical investigations of bond between CFRP and concrete, In: Construction and Building Materials 21, pp. 709–726

Thorenfeld, E. 2002: Anchor capacity of tension loaded CFRP plates bonded to concrete, in Bond in Concrete – From Research to Standards, Proceedings, Budapest, Budapest University of Technology and Economics, pp. 638-647

Zehetmaier, G. 2006: Zusammenwirken einbetonierter Bewehrung mit Klebearmierung bei verstärkten Betonbauteilen (Interactions of embedded and externally bonded reinforcement in strengthened concrete structures), Ph.D-thesis, Technische Universität München, 289 pp. (in German)

Zilch K. Niedermeier R. Finckh W. 2010: Praxisgerechte Bemessungsansätze für das wirtschaftliche Verstärken von Betonbauteilen mit geklebter Bewehrung - Verbundtragfähigkeit unter statischer Belastung (Practice-Oriented Design Approaches for Cost-Efficient Strengthening of Concrete Members Using Adhesive Reinforcement - bond resistance under static loading), DAfStb Heft 592, Beuth Verlag, Berlin, 174. pp (in German)