SPLITTING DESIGN FOR ANCHORAGES AND SPLICES WITH POST-INSTALLED REINFORCEMENT

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ABSTRACT

A detailed design concept for the anchorage length of reinforcement bars has been developed and confirmed by tests.

The ultimate limit state (ULS) design for bond and splitting is derived from ACI 318, chapter 12. This approach allows taking into account the splitting bond strength of a given anchorage, i.e. the bond stress developed along the reinforcement at which the surrounding concrete will split. In fact, the resistance against pullout of a bar cast with the concrete is not necessarily the same as that of a bar set into a drilled hole by means of an adhesive mortar. However, the resistance against splitting of the surrounding concrete is expected to be the same in both cases. Thus the ULS design of the anchorage length takes into account the steel, concrete and bond strengths as well as the geometry of the anchorage or splice.

Special attention has been given to the design provisions for splices. According to most of the current structural codes, the length required for an end anchorage has to be multiplied by a factor of 1.0 to 2.0. The approaches of ACI 318 and Eurocode 2 are compared and a specific design concept taking into account the available confinement around the splice is proposed.

Several series of tests considering the concrete quality, the concrete cover, the transverse reinforcement and the type of anchorage (end anchorage, splice) have been performed to confirm the validity of the proposed design. More tests taken from the relevant literature have also been evaluated with respect to the splitting design concept.

The proposed design concept allows an economical design especially of post installed anchorages and splices where costs arise not only from the amount of steel required, but also for drilling work and the adhesive mortar.

1. INTRODUCTION

Anchorage and splice lengths of cast-in reinforcement bars are defined by the applicable structural concrete design codes. In many cases these anchorage lengths are multiples of the bar diameter or fixed bond stresses. Additional multiplying factor often allow for taking into account different states of stress around the anchorage, splice situations and sometimes the concrete cover and bar spacing dimensions. Splitting and pullout failures, as well as displacement conditions, are covered by the prescribed anchorage lengths.

For strengthening and rehabilitation projects, as well as in specific situations in new construction, post-installed bars are used more and more frequently. These bars are fixed in a drilled hole by means of a bonding agent, often a resin based product. Approvals have proved that with some of these products a performance equal to that of cast-in bars can be achieved. Post-installed bars should meet the same failure and serviceability criteria as cast-in bars.

Splitting is the failure of the concrete surrounding the anchorage because of excessive radial stresses. Since splitting is a pure concrete failure, the design of post-installed bars should respect the same splitting criteria as cast-in bars. A design method for splitting is proposed in section 2.

The other failure criterion for reinforcement bars is pullout. If spacing and edge distances have no influence, the bond strengths of cast-in and post-installed bars may differ considerably. With cast-in bars, the bond strength is mainly a function of the rib geometry while post-installed bars take

their pullout resistance from the characteristics of the bonding agent. These characteristics vary from one product to another. Inclusion of different bond strengths into the design concept is shown in section 3.
Although serviceability is not the subject of this paper, it is important to remind at this point, that the displacements of the anchored bar must be small in order to prevent the formation of excessive cracks. The limits of displacement must be defined according to the serviceability requirements of the applications in question.

2. INTERPRETATION OF THE ACI 318 APPROACH

The American standard ACI 318 (1999) gives an explicit formula for the design of anchorages and splices which considers splitting as a function of concrete cover and bar spacing. The development length of an anchorage is defined as a function of steel and concrete strengths, the bar diameter, the minimum edge distance or spacing and a coefficient taking into account the transverse reinforcement:

$$\frac{l_d}{d_b} = \frac{9}{10} \cdot \frac{f_y}{\sqrt{f_c^{'}}} \cdot \frac{\alpha\beta\gamma\lambda}{\left(\frac{c+K_{tr}}{d_b}\right)} \tag{1}$$

with:
- l_d development length required for steel failure [mm]
- d_b bar diameter [mm]
- f_y specified steel yield strength [N/mm^2]
- f_c specified compressive strength of concrete [N/mm^2]
- α reinforcement location factor (=1.0 in the following developments)
- β coating factor (=1.0 for uncoated reinforcement)
- γ reinforcement size factor (=0.8 for No. 19 and smaller bars; =1.0 for No. 22 and larger bars)
- λ lightweight aggregate concrete factor (=1.0 for normal weight concrete)
- c spacing or cover dimension [mm]. Minimum of either concrete cover c_y, side cover c_x, or ½ of spacing s, according to figure 1.
- K_{tr} factor taking into account the transverse reinforcement

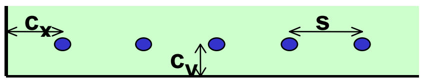

Fig. 1: definition of cover dimension

2.1 Splitting Bond Stress

In the following development we will consider the factors α, β and λ as equal to 1.0 and only consider the bar size factor γ. In strength design, the steel force in a fully loaded bar is

$$F_y = f_y \cdot \Phi \cdot \frac{d_b^2 \pi}{4} \tag{2}$$

with a strength reduction factor Φ=0.9 (ACI 318 (1999)). The bond stress transferring the steel force to the concrete in the anchorage zone is

$$\tau_{sp,d} = \frac{F_y}{d_b \cdot \pi \cdot l_d} \tag{3}$$

The development length l_b is defined as the length, at which the fully loaded bar develops a force equal to the pullout or splitting load. Therefore the bond stress in formula (4) shall be defined as

τ_{sp} (splitting bond stress). Introducing formula (2) for F_y and formula (1) for l_d into (3) the design splitting bond stress is:

$$\tau_{sp,d} = \frac{\sqrt{f_c^{'}} \cdot (c + K_{tr})}{4\gamma \cdot d_b} \quad (4)$$

2.2 Transverse Reinforcement

The ACI 318 code explicitly takes into account the influence of transverse reinforcement able to prevent splitting by the "transverse reinforcement index" K_{tr}:

$$K_{tr} = \frac{A_{tr} \cdot f_{yt}}{10 s_{tr} n} \quad \text{(SI-units)} \quad (5)$$

with: A_{tr} total cross-sectional area of all transverse reinforcement which is within the spacing s and which crosses the potential plane of splitting through the reinforcement being developed [mm^2]

f_{yt} specified yield strength of transverse reinforcement [N/mm^2]

s_{tr} maximum spacing of transverse reinforcement within l_d, center to center [mm]

n number of bars or wires being developed along the plane of splitting [-]

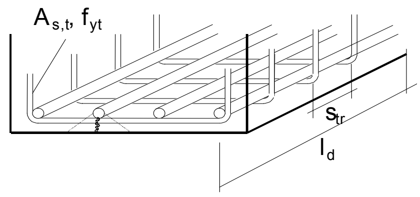

Fig. 2: transverse reinforcement with splitting to surface

Figure 2 shows the influence of transverse reinforcement for the case where splitting is towards the concrete cover. The transverse reinforcement only once crosses a splitting plane; therefore the total area of transverse reinforcement crossing the splitting plane is A_{tr}=$A_{s,t}$ and the number of bars developed along the splitting plane is n=1.

2.3 Limitation of Bond Stress

Formula (1) takes into account pullout failure by limiting the value of

$$\frac{c + K_{tr}}{d_b} \leq 2.5 \quad (6)$$

Thus, for a specified concrete strength of f_c'=20MPa, the bond stress according to formula (4) is limited to 3.49MPa for a bar with diameter smaller or equal to 19.05mm. Figure 3 shows the bond stress as a function of the parameter c/d_b as defined above. The splitting bond stress is defined by the inclined line and increases with greater values of c/d_b. The increase in splitting bond stress is limited by the maximum bond stress, which is a value given by the codes for cast-in bars. For the minimum cover of one bar diameter (c/d_b=1.5), formula (4) gives a maximum bond stress of 2.1MPa.

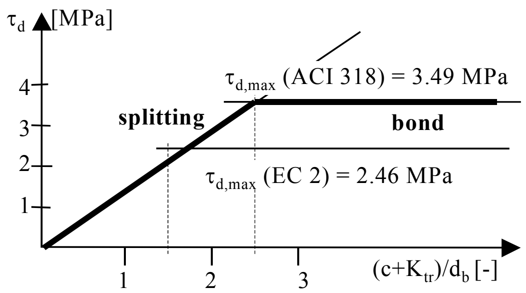

Fig. 3: Splitting and bond strength in different codes for f_c'=20MPa

Other codes, like Eurocode 2 simplify this rule and limit the bond stress to a value at which splitting cannot occur at the minimum spacing and concrete cover defined. Eurocode 2 gives the design bond strength for a concrete C20/25 as

2.3MPa. Taking into account that the average load factor is 1.4 in EC2 and 1.5 in ACI 318, this corresponds to 2.46MPa in figure 3. This value is comparable to the one obtained by the formula for splitting bond stress (4). Therefore, the bond strength given in EC 2 should be considered not as a bond condition, but rather as a splitting condition.

3. MODIFIED APPROACH FOR POST-INSTALLED BARS

For post-installed reinforcement bars, the maximum bond stress is a function of the bonding agent and not necessarily equal to that of cast-in bars. Thus, the limitation for pullout failure in equation (6) should be replaced by the specific design bond stress of a bonding agent. In order to be in line with the design of bonded anchors according to ETAG (2001), a bilinear approach has been chosen: For values of $(c+K_{tr})/d_b$ greater than 2.5, the slope of the splitting curve is reduced by a factor δ, which should be between 0.7 and 0.8. The analytical description of splitting failure thus becomes:

$$if\ \frac{c+K_{tr}}{d_b} \leq 2.5: \quad \tau_{sp,d} = \frac{\sqrt{f_c^{'}} \cdot (c+K_{tr})}{4\gamma \cdot d_b} \tag{7a}$$

$$if\ \frac{c+K_{tr}}{d_b} > 2.5: \quad \tau_{sp,d} = \frac{\sqrt{f_c^{'}} \cdot \left[2.5 + \delta\left(\frac{c+K_{tr}}{d_b} - 2.5\right)\right]}{4\gamma} \tag{7b}$$

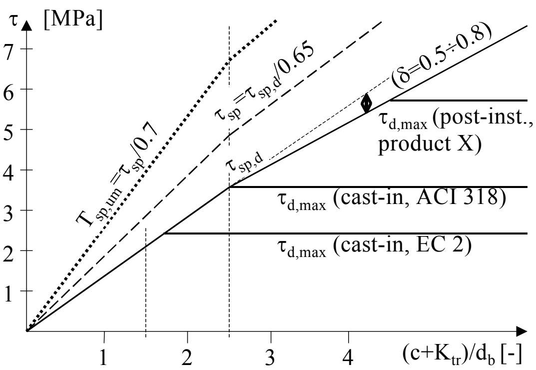

Fig. 4: Splitting and bond strength according to proposed model (size factor γ=0.8, fc'=20MPa)

In section 4, test results are compared with the proposed approach under the following assumptions: The strength reduction factor Φ has been supposed to be 0.65 ($\tau_{sp,d}=\tau_{sp}*\Phi$). This is the value proposed in ACI 318 (1999) for plain concrete. As described in R22.2.2, the integrity of anchorages and splices depends solely on the properties of the concrete in the case where there is no transverse reinforcement. Therefore, this factor should be taken into account. Moreover, it is assumed that the nominal strength is 0.7 times the mean ultimate load ($\tau_{sp}=\tau_{sp,um}*0.7$) (Marti, 1993). The dependence on splitting and bond stress on the factor $(c+K_{tr})/d_b$ is shown in figure 4.

4. TESTS

4.1 Pullout Tests with Small Concrete Cover

Pullout tests from different sources were analyzed and compared to the modified ACI 318 approach shown in figure 4. Most tests with cast-in bars have been taken from the literature, while new tests with post-installed bars were performed. In the analyzed tests, bar diameters range from 10 to 36mm, anchorage lenghts from 140 to 600mm. In some of these tests, the elongation of the steel was measured in different locations of the bars by strain gauges.

Figure 5 shows the bond stresses at splitting failure which were evaluated assuming an uniform stress distribution along the bars and standardized to a concrete strength of 25MPa:

$$\tau_{sp,u} = \frac{F_u}{l_d \cdot d_b \cdot \pi} \cdot \sqrt{\frac{25}{f_{c,test}}} \tag{8}$$

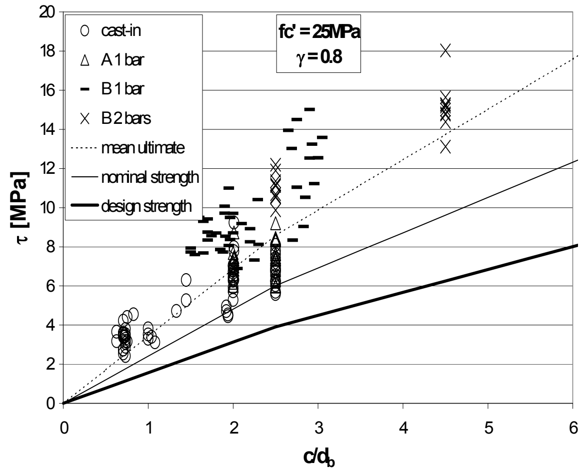

Figure 5 shows that for cast-in bars as well as for post-installed single bars the average splitting bond strength is very accurately predicted by the modified ACI 318 approach as proposed in section 3. The nominal bond strength corresponds in fact to the minimum values observed in the tests and the design strength therefore has the required safety margin. The tests with two bars, with spacings from 75 to 255mm, show even somewhat higher mean ultimate loads.

Fig. 5: pullout tests with small concrete cover

4.2 Transverse Reinforcement

Pullout tests have also been performed with different amounts of transverse reinforcement. The values of K_{tr} have been computed according to ACI 318. Figure 7 shows the test results in comparison to the proposed design approach. While the tests with product B correspond well to the design concept, the results of the tests with product A clearly fall below the expected values. It seems that product A is more sensitive to the micro-cracks which form in order to make the transverse reinforcement work. The beneficial effect of transverse reinforcement can therefore not be taken into account unless the bonding agent has been prequalified correspondingly. With transverse reinforcement, the bond strength to be taken into account has to be suitable for cracked concrete.

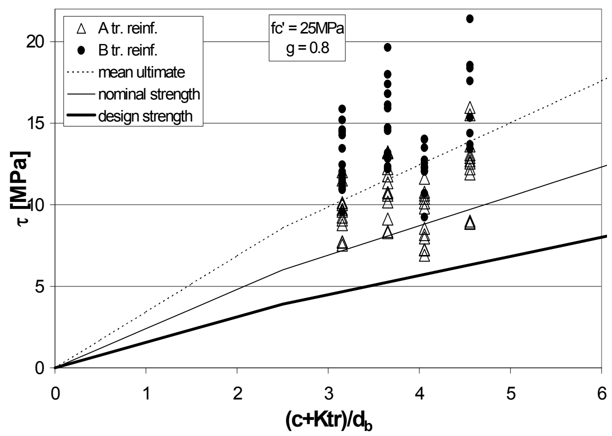

Fig. 7: pullout tests with transverse reinforcement

4.3 Splice Tests

In general, ACI 318 applies a splice factor of 1.3 to the basic anchorage length for steel failure. In Eurocode 2 the splice length is 1.0, 1.4 or 2.0 times the required anchorage length, i.e. it can be adapted with the proportion of required and provided steel area. The multiplying factors depend on the spacing and side cover of the bars. As for post-installed bars it is especially important to optimize the splice length in order to minimize labour and mortar costs, it a splice factor taking into account the effective confinement will be used:

$$f_{splice} = 2 - \frac{[(c+K_{tr})/d_b]-1}{9} \quad ; \quad 1.0 \le f_{splice} \le 2.0 \qquad (9)$$

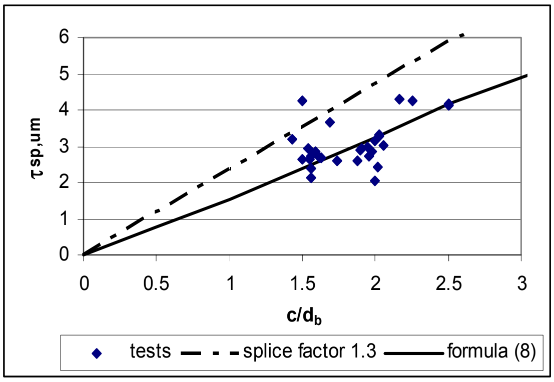

Fig. 8: splice tests

On the safe side, formula (9) assumes that the splice factor can be reduced to 1.0 if the confinement coefficient $[(c+K_{tr})/d_b]$ is larger than 10. Splice tests from Ferguson and Breen (1965) and from Thompson (1975) have been evaluated splitting bond strength according to formula (7) and splice factors according to formula (9) as well as with a constant splice factor of 1.3. The test results are normalized to a concrete strength of f'_c=25MPa. Figure 8 shows that formula (8) gives a clearly better prediction of the test results than the constant splice factor of 1.3. Further research should allow to reduce the quotient of 9 in formula (9).

5. CONCLUSIONS

A design concept taking explicitly into account splitting of concrete and bond of reinforcement has been derived from the provisions of ACI 318, chapter 12. The splice factor is based on the available confinement. Anchorage design according to the new concept is somewhat more costly than with traditional methods, but it has the great advantage of clearly showing the possible failure modes and the achieved safety level. Moreover, it is possible to differentiate between bars with a specific bond strength, which depends on the rib geometry for cast-in, and on the bonding agent for post-installed bars.

The analysis of a large number of tests has shown that the proposed concept is applicable to both cast-in and post-installed bars. Since the behavior of anchorages and splices with post-installed reinforcement therefore on the characteristics of the bonding agent, it is advisable that only products, which have been qualified by specific tests be used with the proposed method.

6. REFERENCES

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