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AN INVESTIGATION ON BOND PERFORMANCE OF HIGH STRENGTH CONCRETE

UNE ETUDE SUR LA PERFORMANCE D'ADHERENCE DES BETONS A HAUTE RESISTANCE

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ABSTRACT : The paper reports the findings of 42 eccentric and concentric pull-out bond tests performed on both high and normal strength reinforced concrete specimens. The data obtained indicated that the essential development length is shorter and the end slip between reinforcing steel and concrete is considerably smaller in high strength concrete than in normal strength one. Also, there was evidence that near ultimate load the ultimate bond stresses in high strength concrete are not as evenly distributed along the anchorage length as in normal strength concrete.

RESUME : Cet article présente les conclusions des 42 essais de traction excentriques et concentriques d'adherence appliqués aux spécimens des bétons à hautes et normales résistances. Les données obtenues ont indiquées que la longueur d'ancrage dans les bétons à haute résistance est plus courte et le glissement à l'extremité entre l'armature en acier et le béton est considérablement plus petit que celui obtenu pour le béton à résistance normale. Aussi, on a observé que à la charge limite, les résistances d'adherence finales dans les betons à haute résistance ne sont pas distribuées uniformément sur la longueur d'ancrage comme dans le cas des bétons à résistance normale.

1. INTRODUCTION

Until quite recently the compressive strength of normal strength concretes (NSC) was generally limited to values less than 60 MPa. It was difficult to use higher strength concretes (HSC) because the dryness of their mix created workability problems. However, with the emergence of ever improved superplasticizers and pouring techniques , this obstacle has been greatly removed, making it easier to pour HSC into forms. Use of HSC in structures brings along many advantages such as smaller cross sections, savings in dead load, greater durability, narrower crack widths.

Anchorage bond is an essential property for all reinforced concrete structures. It has been extensively investigated in reinforced NSC elements and a relatively sound understanding of bond behaviour has been established. The anchorage bond related formulas of the present-day reinforced concrete codes are based on these findings. Whether these rules can be stretched to cover without reservation HSC elements as well is not clear. This paper reports the findings and conclusions of a preliminary experimental study undertaken to investigate anchorage bond behaviour in reinforced HSC elements and to compare it with the corresponding behaviour in NSC elements (1).

2. TESTS UNDERTAKEN

Pull-out tests have been performed on twenty concentrically reinforced and twenty-two eccentrically reinforced concrete prisms with 150x150 mm^2 cross section. The test specimens were made of both high and normal strength concrete (1). A concrete cylinder strength of around 80 MPa was aimed for HSC and 20 MPa for NSC specimens. The test variables were the bar diameter, ∅, the anchorage length, l_b and the thickness of concrete cover. Also web reinforcement has been used in four of the eccentrically reinforced NSC specimens. Reinforcement used consisted of 12, 16 and 20 mm diameter (∅12, ∅16, and ∅20) deformed steel bars. The relative rib areas for these bars calculated according to the CEB formula presented in CEB's Bulletin 151 were 0.09, 0.07 and 0.06 respectively for ∅12, ∅16 and ∅20 bars (2). This identifies them as high bond reinforcement. The anchorage length varied as multiples of ∅ and the concrete cover thickness in eccentrically reinforced specimens were either 15 or 25 mm. The eccentric pull-out test setup used is shown in figure 1. The pull-out force applied to the protruding end of the reinforcement and the slip of steel relative to concrete at both ends of the specimen was measured as shown in figure 2.

3. TEST DATA

The material and geometric properties of the test specimens are reported in tables 1 and 2. Code names for the test specimens are given in the first column. The first letter in the code, either N or H designates respectively NSC or HSC elements. For eccentrically pulled out specimens letter E follows the first letter. Following the letters the first two digits (except for three of the specimens the first digit only) give the anchorage length employed as multiples of ∅. The third digit (except second digit for the three specimens where the anchorage length is specified by the first digit only) designates the reinforcing bar size. Here, 1 stands for ∅12, 2 for ∅16 and 3 for ∅20 bar. The fourth digit appearing in the code names of the eccentrically reinforced specimens gives the concrete cover thickness. 1 stands for 15 mm and 2 for 25 mm thickness. For example : HE1531 designates a HSC, eccentrically reinforced test specimen having an anchorage length of 15∅ mm, ∅20 reinforcement and a concrete cover thickness of 15 mm, or N20-2 designates a NSC concentrically reinforced one having an anchorage length of 20∅ mm and ∅16 reinforcement. In addition, W1 is added to the end of the code names of three of the four web reinforced NSC test specimens having 4 mm diameter closed stirrups spaced at 65 mm. W2 is added to the code name of the remaining one where the web reinforcement was doubled.

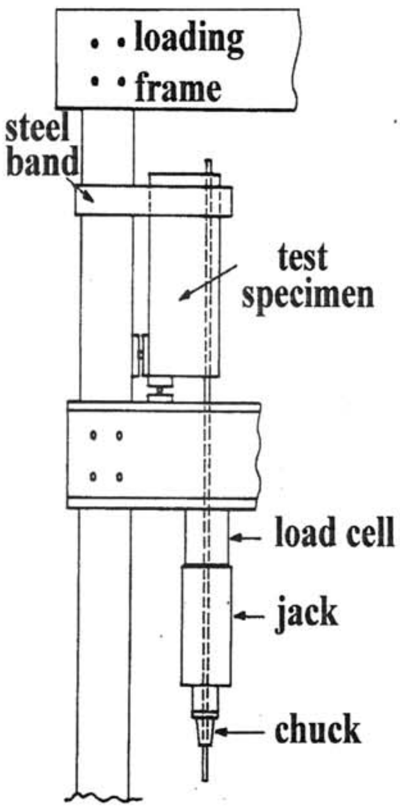

Figure 1 : the eccentric pull-out test setup

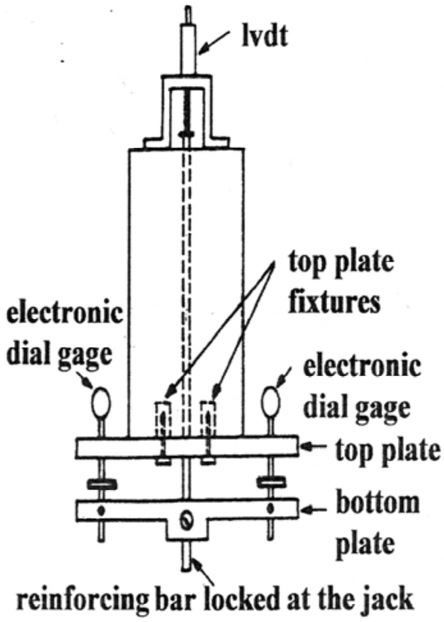

Figure 2 : recording setup in pull-out tests

Table 1 : properties of the concentrically reinforced test specimens

Specimen	f_{yk} (MPa)	f_{ck} (MPa)	f_{cts} (MPa)
H20-1	453	77.8	4.0
H20-2	387	74.1	5.5
H20-3	386	87.1	3.9
H30-1	413	87.4	5.1
H15-1	482	78.9	6.2
H15-2	418	78.9	6.2
H15-3	391	87.6	4.9
H12-1	448	85.4	6.4
H12-2	373	85.4	6.4
H12-3	436	85.4	6.4
H9-3	433	69.9	5.6
H6-3	433	69.9	5.6
H3-3	439	69.9	5.6
N10-3	439	17.3	1.8
N15-1	427	26.4	2.7
N15-2	378	26.4	2.7
N15-3	442	26.4	2.7
N20-1	469	21.7	2.6
N20-2	336	25.1	2.6
N20-3	426	23.7	2.5

Also, 0 is added as a fourth digit to the end of the codes of three specimens in order to indicate that the strength of their concrete is considerably higher than the one aimed for the NSC test specimens. Symbols f_{yk}, f_{ck} and f_{cts} respectively stand for the characteristic yield strength of the steel reinforcement, the characteristic cylinder strength and the split cylinder strength of concrete.

Table 2 : properties of the eccentrically reinforced test specimens

Specimen	f_{yk} (MPa)	f_{ck} (MPa)	f_{cts} (MPa)
HE1511	494	78.9	5.8
HE1521	356	91.3	6.1
HE1531	416	83.5	6.9
HE1211	472	88.3	5.4
HE1221	390	88.3	5.4
HE1231	454	88.3	5.4
HE1212	476	85.3	6.5
HE1222	451	85.3	6.5
HE1232	431	85.3	6.5
HE1011	516	83.9	5.6
HE1021	393	83.9	5.6
HE1031	278	83.9	5.6
NE15110	501	44.3	4.1
NE15210	346	45.1	4.3
NE15310	449	44.3	4.1
NE1511	535	22.9	2.7
NE1521	394	22.9	2.7
NE1511W1	552	19.2	2.2
NE1521W1	378	19.2	2.2
NE1531	436	13.8	1.8
NE1531W1	463	12.8	1.8
NE1531W2	463	13.8	1.8

Most of the tests ended up by yielding in steel, while some bond failures through splitting in concrete were observed. Also, four of the eccentric pull-out tests ended by diagonal tension failure due to shear. The final pull-out force and the type of failure observed during the tests is reported in tables 3 and 4 for each specimen. In the last column of each table Y stands for yielding, S for splitting and DT for diagonal tension failure. The average ultimate bond stresses for the tests that ended up by bond failure are also given. They are calculated by dividing the pull-out force by the product of anchorage length and reinforcing bar perimeter. These stresses are normalized with respect to concrete strengths of 20 MPa for NSC and 85 MPa for HSC in order to remove the effect of strength variation among test specimens.

In all tests slip between reinforcement and concrete at the loaded end of the specimen started under very low pull-out forces and increased somewhat linearly with increasing force. No significant slip was recorded at the unloaded ends of the specimens. Some of the typical loaded end steel stress-slip and average bond stress-slip relations observed during the tests are given in figures 3,4,5 and 6. Here, the loaded end steel stress is determined by dividing the pull-out force by the cross-sectional area of steel.

4. INTERPRETATION OF THE TEST DATA

Figure 3 shows that when the anchorage length is enough to prevent bond failure prior to yielding in steel, the slip between steel and concrete at the pulled end increases linearly with steel stress and is independent of anchorage length. Figure 4 and 5 show that this slip is considerably greater in NSC specimens than in the HSC ones. As seen in figure 6 slip in NSC specimens decreases with the use and increase of web reinforcement.

It is observed in tables 3 and 4 that except for H12-1 all HSC test specimens having anchorage lengths of 10∅ or longer ended up by yielding in their reinforcement and those with shorter anchorage lengths failed in bond. The bond failure observed in specimen H12-1

Table 3 : test results - concentric pull-out tests

Specimen	Pull-out force (N)	Average ultimate bond stress (MPa)	Failure by yielding or splitting (Y) or (S)
H20-1	46695		Y
H20-2	68670		Y
H20-3	122625		Y
H30-1	47480		Y
H15-1	46892		Y
H15-2	65727		Y
H15-3	125372		Y
H12-1	47285	8.6	S
H12-2	65138		Y
H12-3	123998		Y
H9-3	78872	7.6	S
H6-3	64118	9.3	S
H3-3	24848	7.2	S
N10-3	65638	5.5	S
N15-1	46696		Y
N15-2	74556	5.3	S
N15-3	113796	5.2	S
N20-1	44537	4.7	S
N20-2	66512		Y
N20-3	123017	4.4	S

Table 4 : test results - eccentric pull-out tests

Specimen	Pull-out force (N)	Average ultimate bond stress (MPa)	Failure yielding splitting or shear (Y,S,DT)
HE1511	52974		Y
HE1521	68670		Y
HE1531	117720		DT
HE1211	51012		Y
HE1221	67100		Y
HE1231	98100		DT
HE1212	48461		Y
HE1222	76518		Y
HE1232	117720		DT
HE1011	49325		Y
HE1021	70946		Y
HE1031	127864		Y
NE15110	49050		Y
NE15210	67885		Y
NE15310	100062		DT
NE1511	49128		Y
NE1521	68297		Y
NE1511W1	46666		Y
NE1521W1	65639		Y
NE1531	79294	5.0	S
NE1531W1	81384	5.1	S
NE1531W2	88398	5.5	S

was an exception. It should be evaluated with reservation since other specimens with shorter anchorage lengths and larger bar diameters had all ended with yielding in their steel. Ignoring this exception a limiting anchorage length of 10∅ seemed to be adequate for HSC elements under monotonic loads provided that the reinforcing bar size is limited to 20 mm diameter or less and concrete cover thickness is 15 mm or more. Needless to say, critical factors that increase the anchorage length requirement like close spacing of longitudinal reinforcement, repetition and reversing of loads and safety factors have not been given any consideration in this conclusion.

Test specimens H3-3, H6-3 and H9-3 were poured from the same batch of concrete and were all reinforced with ∅20 bars but had anchorage lengths 3∅, 6∅ and 9∅ respectively. As reported in table 3, they all ailed in bond by splitting. For these specimens, the average ultimate bond stresses calculated were respectively 7.2, 9.3 and 7.6 MPa. Here the intensity of the average ultimate bond resistance is relatively low for the short anchorage length, relatively high for the medium one and somewhat lower for the longer anchorage. This variation in the intensity may be an indication for the non-uniformity of the bond stress distribution along the anchorage length in HSC specimens. Azizinamini et al. presented evidence supporting this supposition as well (3). Hypothetically, let a nine bar diameter anchorage length be divided into three segments, each segment having a length of 3∅. If it is assumed that the first segment at the loaded end carries a force equal to the capacity of H3-3, the second segment, the difference in capacity between H6-3 and H3-3 and the last segment difference in capacity between H9-3 and H6-3, the distribution shown in solid lines in figure 7 is obtained. Taking this force distribution as basis, the probable bond distribution can be sketched as shown in dotted lines in figure 7. The authors think that it may be worth investigating bond stress distribution in HSC along these lines.

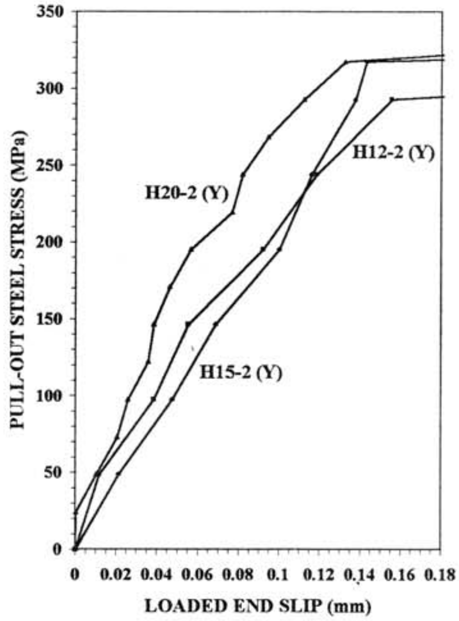

Figure 3 : pull-out steel stress-slip relation

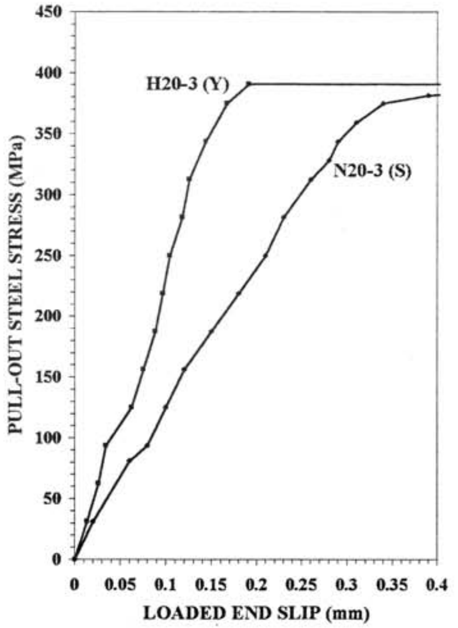

Figure 4 : pull-out steel stress-slip relation for NSC and HSC

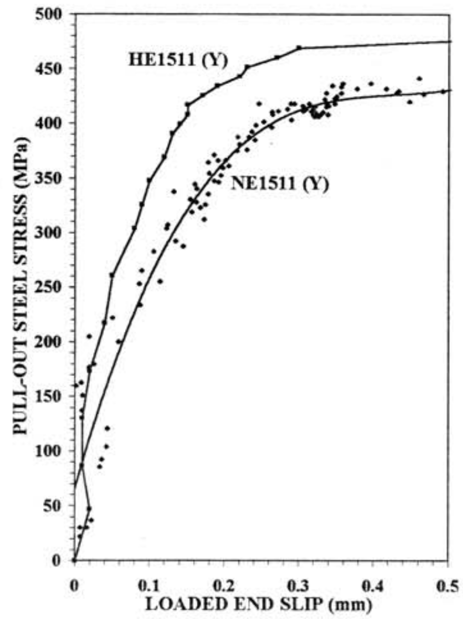

Figure 5 : pull-out steel stress-slip relation for NSC and HSC

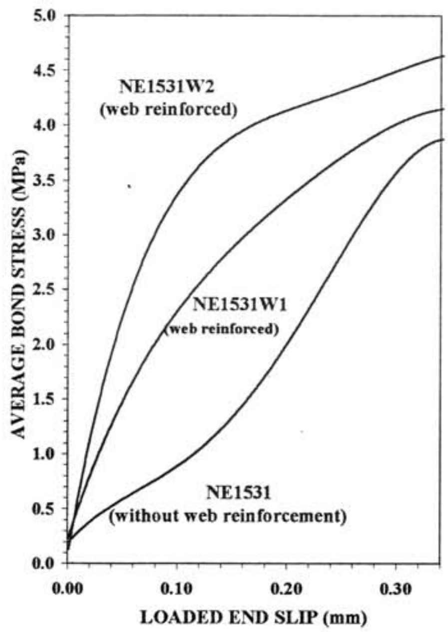

Figure 6 : average bond stress-slip relation

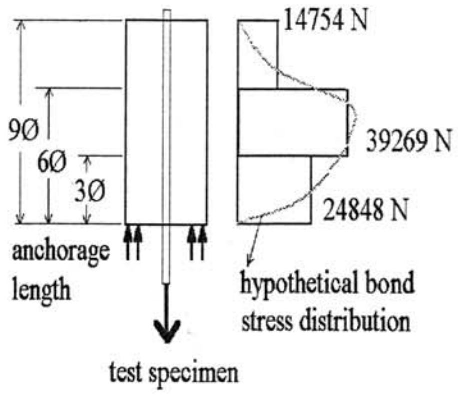

Figure 7 : hypothetical bond stress distribution

5. CONCLUSIONS

The limited number of tests reported in this study hinted the following characteristics about the bond behaviour in reinforced HSC elements.

1. Under the same loading the end slip between reinforcing steel and concrete is considerably smaller in HSC elements than in the NSC ones. That means crack widths will be smaller in HSC than in NSC since a similar slip mechanism causes widening in cracks.

2. There is evidence that at the ultimate state the bond stresses vary appreciably along the anchorage length in HSC elements. Therefore, caution should be exercised while trying to stretch the anchorage length formulas based on findings of bond behaviour in NSC where a more uniform bond stress distribution prevails.

3. Under monotonic loads, an anchorage length of 10∅ for HSC and 20∅ for NSC elements reinforced with a single 20 mm bar or smaller seems to be satisfactory.

4. Bond failure by splitting in concrete takes place rather suddenly with a burst in HSC while it is less brittle in NSC.

Since influencial factors like load repetition and reversal, reinforcement spacing and deflections have not been considered during the tests, these conclusions should describe the qualitative bond behaviour in HSC elements as compared to NSC ones more than establishing any quantitative results.

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