Development of a novel bond test set-up for concrete with transverse reinforcement

DEVELOPMENT OF A NOVEL BOND TEST SET-UP FOR CONCRETE WITH TRANSVERSE REINFORCEMENT

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Abstract

Bond between reinforcing steel and concrete is essential for the combined action of the two materials and the overall resistance of reinforced concrete structures. The bond strength of embedded bars depends on the stress-state of the concrete surrounding the reinforcement. However, existing bond test recommendations typically induce transverse compressive stresses from the support reactions on the bond region, affecting the results and limiting the applicability of the empirical models that are derived. To overcome this parasitic effect, a novel cantilever bond test set-up was developed and validated experimentally. A new specimen geometry with a protruding nib was developed to remove spurious support compressions from the bonded region. The resulting geometry has similarities with that of half-joint beam ends. The longitudinal bars were pulled-out of the full-depth section. Due to the distribution of internal forces, the transverse reinforcement was simultaneously subjected to tensile stresses. The presence of transverse reinforcement limited the opening of longitudinal cracks and the subsequent reduction in bond strength. The new test method leads to a better understanding of the fundamental aspects that underpin bond and anchorage in reinforced concrete. It also allows parameters useful for design and assessment calculations to be evaluated more accurately.

Keywords: Anchorage, confinement, dapped-end, half-joint, standard, test.

1. Introduction

The load-carrying capacity of reinforced concrete structures relies on the combined action of the concrete and the internal reinforcing bars, conventionally made of steel (Ritter 1899, Mörsch 1906). To ensure the transfer of forces between the two materials, the reinforcement has to be anchored in the concrete. This can be done locally with plates, bends or other anchorage devices. Alternatively, a gradual transfer of forces can be achieved after the so called development length of straight bars. The compatibility of strains between the two materials is ensured by bond. From a conceptual point of view, bond can be interpreted as the progressive change in tensile force along the bar per nominal unit area of contact surface between the steel and the concrete (Tepfers 1979, fib 2000, Cairns & Plizzari 2002). This concept is approximately correct for smooth bars. For deformed bars, the main resisting mechanism relies on the interlock between steel ribs and concrete lugs. The simplification of distributed bond stresses is known to be inaccurate but it is useful for design, especially for prescriptive codified approaches. However, the underlying resisting mechanisms are complex and Cairns & Plizzari (2003) acknowledged that a single measure of performance is inadequate to characterise bond behaviour. A system of tests is required. Moreover, they recognise that a standard test may not reproduce exactly a practical configuration but a correlation with structural performance in real situations is necessary.

There is a general consensus that transverse confinement plays a significant role in the bond behaviour of reinforcement, for both smooth and ribbed bars (Bigaj, den Uijl & Walraven 1996, den Uijl & Bigaj 1996, Gambarova, Rosati & Zasso 1989, Giuriani, Plizzari & Schumm 1991, Plizzari, Deldossi & Massimo 1998, fib 2000, Cairns & Plizzari 2003, Lin & Zhao 2016). It follows that particular attention should be devoted to the confining effects in the recommendations for standard bond tests. Gambarova, Rosati & Zasso (1989) carried out bond tests on specimens where splitting cracks were pre-formed, and the transverse confining force was controlled with a steel frame. They concluded that transverse confinement plays a crucial role in the post-cracking phase. Desnerck, Lees & Morley (2015) investigated the bond behaviour of cracked concrete. They carried out concentric pull-out tests on pre-cracked cylinders with an embedded ribbed steel bar. The impact of confinement was also investigated, consisting of an outer concrete sleeve cast around the cracked cylinders or an external plastic tube. They observed that confinement influences the bond behaviour of pre-cracked specimens, restraining longitudinal cracks from opening. Lin & Zhao (2016) studied the effects of confinement on the bond behaviour of corroded steel bars. They carried out accelerated corrosion and bond tests on beam specimens, where a plastic tube around the bars was used as a debonding sleeve within the specimens over the supports. They concluded that confinement plays an important role in the bond behaviour of reinforcing bars. They observed that bond degradation was limited by the presence of transverse reinforcement and increasing cover/diameter ratios, thanks to residual tensile strength of cracked concrete surrounding the bars.

Confinement can consist of concrete around the bar, transverse reinforcement, external restraints or forces applied to the specimen. Of particular interest is the impact of transverse pressure providing external confinement to the bonded region of reinforcing bars. Baldwin & Clark (1995) carried out eccentric bond tests on unconfined prismatic specimens to investigate the effects of reduced anchorage lengths. They used a plastic tube as a debonding sleeve over one support. However, they reported that the sleeve was not fully effective as it provided a residual bond resistance. In their accelerated corrosion and eccentric pull-out tests, Zandi Hanjari, Coronelli & Lundgren (2011) used a specimen geometry that replicated the shape of a beam end after the formation of an inclined shear crack, previously developed by Magnusson (2000). Despite the use of debonding sleeves over the supports, they reported that the influence of the reaction pressure on bond stresses close to the support region was substantial. Their observation was supported by a Nonlinear Finite Element Analysis of the tests. To avoid the influence of support pressure on the anchorage behaviour of corroded bars, Lundgren et al (2015) developed an 'indirectly supported' four-point bending experimental set-up. They tested reinforced concrete beams removed from a bridge that had been in service for over 30 years, investigating the anchorage behaviour of naturally corroded reinforcing bars. The supports were obtained by drilling transverse circular holes on the upper portion of the beam ends, suspending the specimens. However, the beam ends had to be strengthened with hangers, consisting of steel bars post-fixed vertically into the concrete on either side of the holes.

A review of the relevant literature suggests that transverse pressure from the supports provides additional external confinement and increases bond strength. Current test methods are not effective in eliminating this parasitic effect. This limitation of the existing test set-up indicates the necessity for a new and improved methodology. To this end, a new bond test arrangement was developed.

2. Test Design

A new bond tests was developed and validated experimentally. Pull-out bond trial tests were conducted on two specimen geometries where the bottom concrete cover was varied. The characteristics and properties of the two specimens are summarised in Table 1.

Table 1. Test Matrix

	Specimen A	Specimen B
Specimen height [mm]	380	400
Bottom cover [mm]	50	70
Side cover [mm]	50	50
Bar diameter [mm]	16	16
Bond length [mm]	80	80
Rib height [mm]	1.25	1.60
f_c [MPa]	21.75	28.15
$f_{c,cube}$ [MPa]	36.02	34.54
$f_{ct,split}$ [MPa]	2.79	2.58

2.1. Specimen Geometry

The specimens were concrete beam-ends. The geometry of the specimen is a modification of the prismatic cantilever test (Kemp, Brezny & Unterspan 1968) to induce a concrete stress field similar to that developed on the underside of flexural beams, without the parasitic effect of support pressure. A protruding nib is introduced on the unloaded (passive) side of the pull-out bar, where the support reaction is located, to move support pressures away from the bonded region. The pull-out bars are located at the bottom of the full-depth section. The segments adjacent to the bond length were debonded by removing the ribs of the reinforcement bars and providing a debonding sleeve made of masking tape. On the loaded (active) side of the pull-out bar, the specimen has an inclined face, similarly to the geometry proposed by Magnusson (2000). In addition to replicating the shape of a bending-shear crack of a conventional beam, this geometry allows the length of debonding sleeves to be minimised. The specimens are reinforced with ribbed steel bars in both the longitudinal and transverse (shear links) direction. Vertical shear links provide confinement to the pull-out bars. The geometry and dimensions of the specimens are shown in Figure 1:

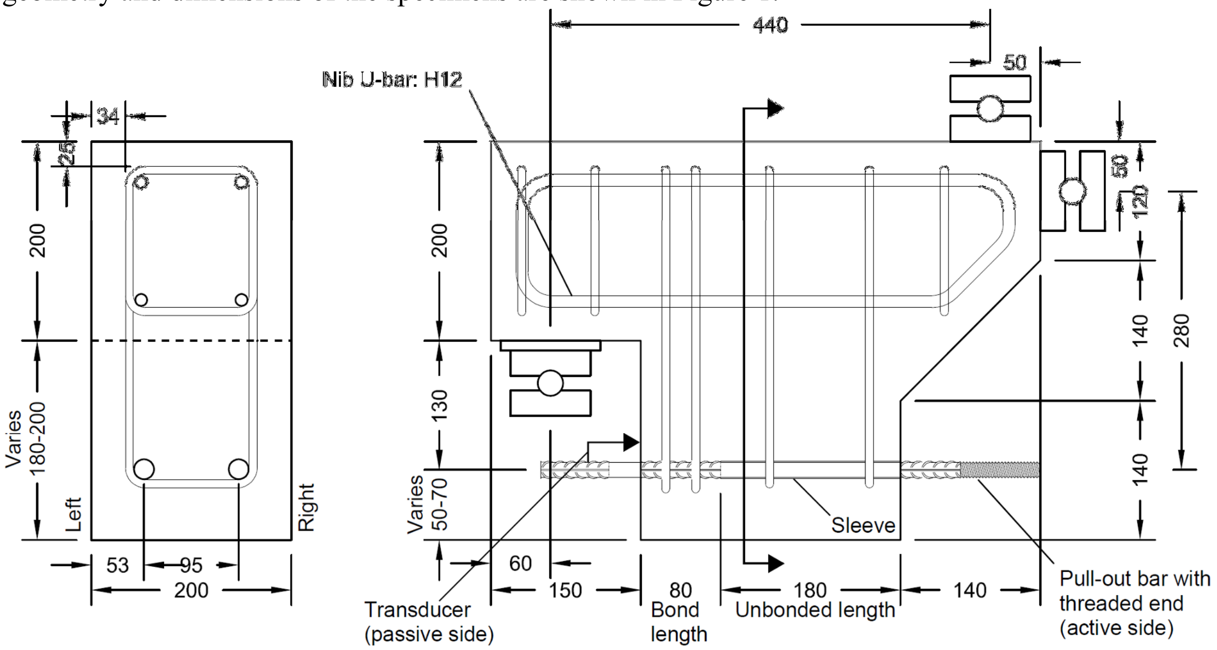

Figure 1. Geometry of the specimens (dimensions in mm).

2.2. Strut-and-Tie model

The design of the specimens was carried out using a Strut-and-Tie Model (STM) (Schlaich, Schäfer & Jennewein 1987, Schlaich & Schäfer 1991, Collins & Mitchell 1991, MacGregor 1992, fib 2013, Goodchild, Morrison & Vollum 2014) and a Finite Element Analysis (FEA), before being validated experimentally. The position of the pull-out bar was chosen as a critical location corresponding to a Compression-Tension-Tension node in the STM, as shown in Figure 2. In design provisions, the strength of this type of node is penalised more than other configurations, due to the limited amount of confinement when more than two tension elements converge to a node (Desnerck, Lees & Morley 2018).

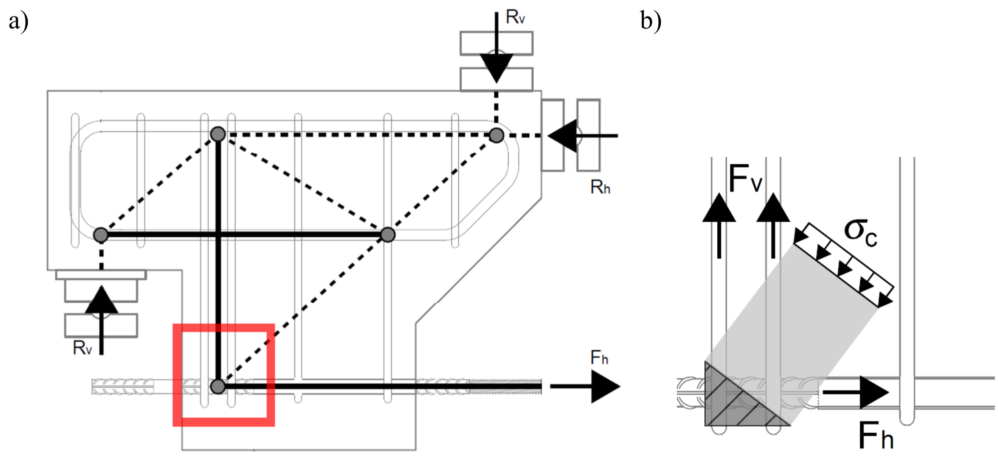

Figure 2. Specimen design: a) Strut-and-tie model, b) Isolated compression-tension-tension node at the location of pull-out bar.

3. Experimental Programme

The novel bond test was validated experimentally. A total of four trial tests were carried out. For each specimen, two bars were tested individually. The geometrical and mechanical characteristics of the experiments are hereby described.

3.1. Materials

The concrete was a C25/30 Ordinary Portland Cement (OPC) mix with no admixtures. Fine aggregate consisted of river sand, coarse aggregate was uncrushed coarse gravel with a maximum aggregate size of 10 mm. The mix composition and proportions of constituents are summarised in Table 2. At 28 days after casting, material characterisation tests were carried out in accordance with and EN 12390-3:2009 and EN 12390-6:2009 to obtain the following control parameters: f_c: compressive strength of concrete cylinder (dia: 100 mm, height: 200 mm); $f_{c,cub}$: compressive strength of 100 mm concrete cubes and $f_{ct,sp}$: split tensile strength of concrete cylinder (dia: 100 mm, height: 200 mm). On average, the 28 day concrete cube strength was 35.3 MPa with a Standard Deviation (SD) of 1.00 MPa, the cylinder strength was 25.0 MPa (SD: 3.61 MPa) and the split tensile strength was 2.68 MPa (SD: 0.29 MPa).

Table 2. Concrete composition.

Constituent	Type	Density	Amount
		[kg/m^3]	[kg/m^3]
Water	-	1,000	180
Cement	CEM II-A-LL 32.5 R	3,100	300
Fine Aggregate	0/4 mm	2,625	835
Coarse Aggregate	4/10 mm	2,625	1,015

The reinforcement consisted of ribbed bars made of high-strength hot-rolled steel. All vertical shear links were H10 bars, and the flexural U-bar at the nib was a H12. The longitudinal bars of the full-depth section subjected to bond testing were H16. Their rib height was 1.25 mm for specimen A and 1.60 mm for specimen B, and the relative rib area (or bond index) f_R was 0.075 and 0.103 respectively, measured according to ISO 15630-1:2010.

3.2. Mixing, Casting and Curing

Fresh concrete was mixed using a mixer with a capacity of 100 litres. The specimens were cast into a plywood formwork, compacted on a vibrating table and immediately covered with plastic sheets. The specimens were removed from the formwork at least 24h after casting, covered in plastic sheets and left to cure in an indoor environment. The curing conditions were uncontrolled. After the standard curing period of 28 days, the plastic sheets were removed before testing.

3.3. Pull-out Tests

The specimens were tested 28 days after casting. The reaction frame consisted of hot-rolled steel beams, assembled with bolted connections and anchored to a concrete strong floor. The specimens were tested upside down with respect to the casting position. The pull-out force was applied with a hydraulic jack and controlled with a tension load cell. Each of the two longitudinal bars was tested individually. The slip between bar and external concrete surface was measured with a Linear Potentiometric Displacement Transducer (LPDT) clamped on the passive end of the bar, as shown in Figure 1. A photograph of the testing arrangement is shown in Figure 3.

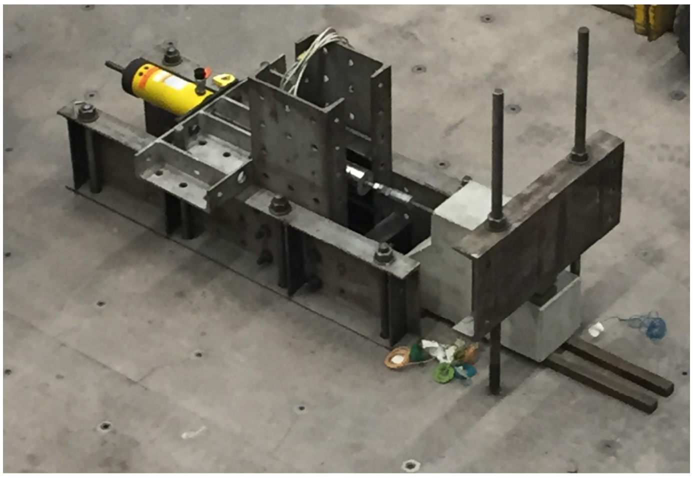

Figure 3. Test set-up.

4. Results

The test results are here presented in terms of equivalent bond stresses and slip, measured between the reinforcing bar and concrete surface on the passive end. The bond stress τ is calculated as follows:

$$\tau = \frac{F}{\pi \cdot \varnothing \cdot l_b} \tag{1}$$

Where F is the pull-out force, $\varnothing$ is the nominal diameter of the bar and the bond length $l_b(s)$, initially equal to $l_{b,0}$= 80 mm (five times the nominal bar diameter), was reduced as the slip s increased during the test to account for the progressive disengagement of the ribs along the bond length:

$$l_b(\mathrm{s}) = l_{b,0} - s \tag{2}$$

The bond stress-slip curves for all tests are shown in Figure 4. The black curves correspond to specimen A and the grey ones to specimen B. The solid lines indicate the first pull-out test carried on a given specimen (right side, indicated by the final letter ‘a’ in the specimen name) whereas the dashed lines show the second test (left side, indicated by the letter ‘b’). Consistently with bond test results from other researchers (Baldwin & Clark 1995, Almusallam, Al-Gahtani & Aziz 1996, fib 2000, Zandi Hanjari, Coronelli & Lundgren 2011, Desnerck, Lees & Morley 2015, Lin & Zhao 2016), the plots exhibit an initial stage of linear proportionality, a progressive reduction in stiffness due to the stable development of cracking, the attainment of a peak strength, a subsequent drop in resistance due to the unstable development of cracking and a residual resistance that decreases gradually as the slip increases. The results from different tests are shown and compared in Table 3. In particular, two values are of interest, based on the RILEM (1994) recommendation: the ultimate bond stress τ_R, corresponding to the peak value measured during the test, and the characteristic bond stress τ_M, calculated as the mean value of bond stresses at slips of 0.01, 0.10 and 1.00 mm. On average, the ultimate bond stress measured during the tests was $\tau_u = 21.4$ MPa (SD: 1.24 MPa).

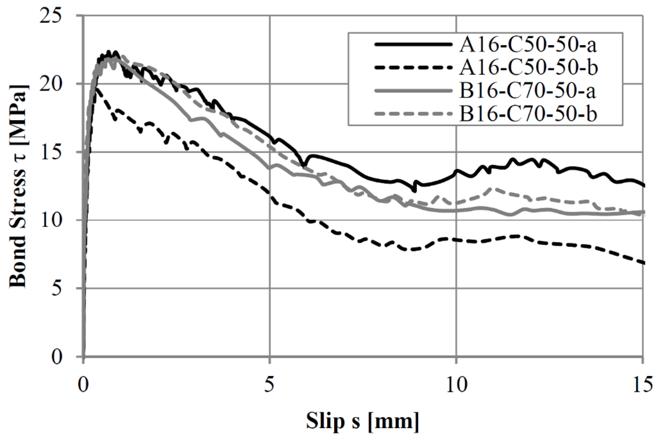

Figure 4. Nominal bond stress-slip curves for different pull-out tests.

Table 3. Summary of test results.

	A16-C50-50-a	A16-C50-50-b	B16-C70-50-a	B16-C70-50-b
Ultimate bond strength τ_R [MPa]	22.3	19.6	21.8	22.0
Slip at ultimate strength s_R [mm]	0.67	0.33	0.67	1.06
Characteristic bond strength τ_M [MPa]	12.98	10.93	14.01	14.23
Bond strength at 0.01 mm $\tau_{0.01}$ [MPa]	4.55	2.65	6.25	4.90
Bond strength at 0.10 mm $\tau_{0.10}$ [MPa]	12.82	12.21	14.21	15.85
Bond strength at 1.00 mm $\tau_{1.00}$ [MPa]	21.57	17.92	21.56	21.95

The force in the transverse reinforcement was also recorded from the strain gauges at the location of the longitudinal reinforcement. The readings indicate that the transverse reinforcement located at the bonded length remained elastic. The strain in the transverse reinforcement remained below 0.15%, below the yield point of the steel. The peak force in the transverse steel and peak pull-out force in the longitudinal bars were not reached simultaneously. The force in the confining reinforcement reaches its maximum value at a slip approximately 0.8 mm greater than that corresponding to the maximum pull-out force.

5. Discussion

The results from the trial tests indicate that the specimen geometry, experimental set-up and methodology are adequate to test longitudinal bars in bond pull-out. The similarity between results suggests the repeatability of the test. The difference in rib height and bottom cover between the two specimens does not appear to have an impact on the results. The surface cracking pattern indicates that the tests failed by splitting of the concrete cover. The concrete cover cracked on the bottom and side faces of the specimens. As an example, a photograph of the cracking pattern for the test A16-C50-50-a is shown in Figure 5. The extent of surface cracking between the two longitudinal bars was limited. This suggests that the combination of bar sizes, distance between longitudinal bars, specimen dimensions, concrete cover, material properties and testing arrangement were sufficient to limit the interaction between the two longitudinal bars.

After the ultimate resistance was attained, residual bond strengths were observed in the experiments. The presence of internal transverse reinforcement limited the crack opening and the subsequent reduction in bond strength. The strain gauge readings indicate that the shear links did not yield, suggesting that a further optimisation of the reinforcement could be performed. Not all parameters have been tested and validated. Before finalising the development of a new standardised bond test, more research is necessary to investigate the effects of parameters such as concrete strength and quality, bar sizes, concrete cover and cover/diameter ratios, different failure modes and cracking pattern.

The similarities between the new specimen geometry and half-joint beams suggest that longitudinal bars are particularly vulnerable to bond failure in half-joints, due to the absence of direct supports and transverse compressive stresses that enhance the confinement in the anchorage region.

Figure 5. Cracking pattern for test A16-C50-50-a.

6. Conclusions

The bond behaviour of ribbed steel bars in reinforced concrete in the presence of transverse reinforcement was investigated experimentally. A new test method was developed, designed and validated experimentally. 4 pull-out bond tests were carried out on steel bars. The following conclusions are drawn:

i. The novel test method was validated experimentally. The set-up allowed longitudinal bars to be tested in bond, eliminating the direct support pressure from the reactions.
ii. Transverse reinforcement provided confinement. The stresses in the transverse bars did not reach the yielding of the steel.
iii. Multiple surface cracking developed on the bottom and side faces of the concrete.
iv. Limited cracking between the two bars was observed. This suggests that the combination of bar sizes, axis distance, cover, material properties and transverse reinforcement is sufficient to test the two bars independently, with limited interaction between the two bars.
v. More research is necessary to derive predictive models and validate the results for different bar sizes, concrete grades, cracking patterns and cover/diameter ratios.
vi. The longitudinal bars in the bottom side of the full-depth section of half-joints are vulnerable to anchorage failure, due to the absence of direct transverse compressive stresses from the support reactions.

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