

EXPERIMENTAL EVALUATION OF THE DIRECT TENSION - PULLOUT BOND TEST

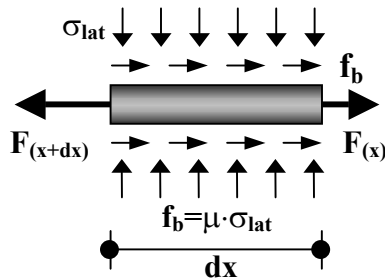
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SUMMARY

This paper presents results of an experimental investigation of the performance of an alternative bond test known as DTP-BT (Direct Tension Pullout Bond test) designed to quantify the lower bound bond properties of steel and GFRP bars embedded in normal strength concrete. Objective of an alternative test setup was to simulate the stress field that develops in the concrete cover surrounding the reinforcement in the tension zone of flexural elements. Parameters of the experimental investigation were, the axial stiffness of the bar and the amount of external confinement. Conventional pullout and beam-splice tests were also done for comparison. It was demonstrated that the most adverse conditions for bond, which occur when the cover concrete is under a direct tension stress field, result in bond properties that differ substantially from those obtained by most established conventional bond tests.

1. INTRODUCTION

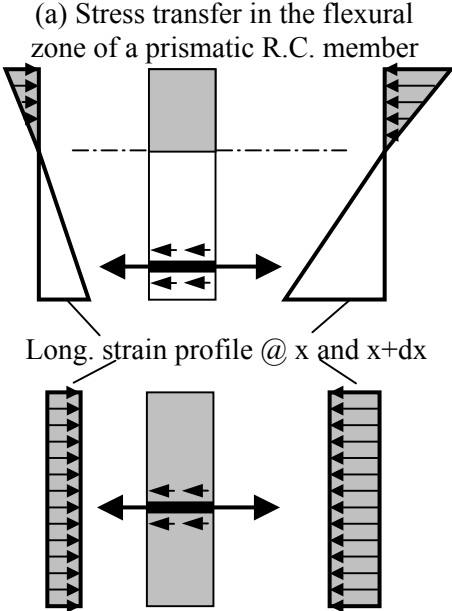
The simplest model representing the stress transfer between steel and concrete is the so-called “frictional concept”, whereby the shear stress that develops along the lateral surface of the bar, (i.e. the bond stress), is a function of the normal confining pressure exerted by the surrounding concrete on the bar surface (Fig. 1). Although a crude representation of the local stress concentrations around the ribs that engage in concrete, in a smeared sense, the simple frictional model properly identifies the significance of many important design parameters for bond: the higher the normal pressure, the higher the frictional force required for pullout and the higher the strength reserves of the splitting failure mechanism. Confinement may be provided by the cover concrete (supported by hoop tension stresses in the cover), by transverse reinforcement crossing the splitting crack path, and by transverse compressive stress fields existing in the anchorage region.



*Fig. 1: Frictional Model
for Bond: $f_b = \mu \cdot \sigma_{lat}$*

Of the three mechanisms contributing to σ_{lat} in Fig. 1, the most difficult to control in conventional bond tests appears to be the magnitude of transverse compressive stress. Because bond is a measure of interaction between concrete and the bar rather than an intrinsic bar property, experimental measurements are affected by the state of stress generated in the bond specimen by the combination of support and loading conditions. For example, spurious inclined compression stress fields are known to occur in the classical pullout specimen from the bearing face at the support of the specimen back to the anchorage zone. The stress-state thus produced in the concrete surrounding the bar bears little relevance to that occurring in the tension zones of flexural elements (Fig. 2, 3). Apart from the normal pressure generated by the pullout specimen on the lateral surface of the bar, the concrete surrounding the bar is

placed under longitudinal compression (Fig. 2(b)) contrary to the actual circumstances of tension reinforcement shown in Fig. 2(a) which is surrounded by concrete in tension. As suggested by the frictional model of Fig. 1, a large range of plausible bond strengths may be generated in the laboratory given the material properties and the cover to diameter ratio, by adjusting the state of stress in the concrete cover.



(a) Stress transfer in the flexural zone of a prismatic R.C. member
 (b) Stress transfer in the classical pullout specimen (Shaded areas=in long. compression; blank areas=in Tension)

Fig. 2: Differences between strain conditions of the concentric and eccentric pullout tests

Several test setups partly or totally different from the conventional direct pullout test have been proposed todate, aiming to generate realistically adverse stress conditions along the anchorage of the test bar. In general, the resulting bond-slip curves differ among specimen types, particularly with regards the deformation capacity of the anchorage, highlighting the need for the establishment of a uniformly accepted test method (Malvar 1992, Bonacci and Marquez 1994, Gambarova et al 1989, Larrard et al 1993, Cosenza et al 1999). In all cases, confinement appears to be a binary effect for most test-setups, particularly when long anchorages are of interest. The need for adopting a harmonized bond test so as to ensure uniform methods for measuring bond is a leading objective of international regulating bodies (ACI408, FIB TG4.3), particularly with regards to the objective of classifying reinforcing bar products. A prevailing test protocol that is gaining ground over the conventional pullout test is the so-called “beam-end” specimen, also known as “eccentric pullout” test, illustrated in Fig. 3 (Cairns 2001, Chana 1990). In this specimen type the lead-in length is in a flexure-shear tension zone as would occur in a realistic situation of a beam shear span. The spurious confining action is influencing only the tail end of the anchorage and would therefore affect performance in the post peak branch, once slip of the front end is significant and bond transfer is moved towards the end of the embedded length. (Note that there is no requirement in a beam-end specimen that the bonded length be so long as to be intercepted by the compression strut; however, in that case, the specimen cross section need be over-dimensioned to the extent that the unreinforced tension zone be able to sustain a tension force equal to that developed by the bar. Therefore, the longer the development length under investigation, the larger would be the required size of the specimen width). The only point of concern in a beam end specimen is that the rate of bond transfer is controlled externally by the shear span and by the imposed curvature along the bar (equal to the beam curvature) rather than being a response parameter as illustrated in Fig. 3(a). (Note that bar curvature has a dual influence on bar bond transfer capacity: as in the case of prestressing tendons, additional frictional action is generated along the contact length, whereas the cover concrete is forced to premature splitting in response to the pressure exerted by the deflecting bars).

It appears that even more critical to the conditions of an eccentric pullout specimen can be generated if anchorage is forced to occur in the presence of a uniformly tensile stress field (i.e. a biaxial tensile stress field without the simultaneous influence of a sharp strain gradient on the specimen cross section) and without the obscuring influence of bar curvature (as in the

case of the common beam lap-splice test). This objective is pursued in the present paper by the design and testing of an alternative bond specimen type, referred to in the remainder as Direct Tension Pullout Bond Test (DTP-BT). The test aims to capture a low bound of bond strength that may be supplied by the concrete cover (without the unaccountable effects of bar curvature), and is appropriate both for steel and FRP reinforcement. The proposed pullout specimen comprises a concrete cylinder with a concentric test bar anchored end to end with a support bar without splicing (Fig. 3(c)). The cylindrical pattern is the most representative to produce test data, used as input verification of the thick walled cylinder model (Tepfers 1979, Cairns 1979) because of the uniform peripheral boundary conditions – stress and geometry (constant cover thickness in every direction). Furthermore, the cylindrical pattern of the specimen is compatible with the lower bound concept because the cover simulates the distance of the bar to the nearest free surface of an actual structural member.

Experimental evaluation of the proposed test setup included testing over 30 DTP-BT long anchorage specimens of medium strength concrete with a pullout bar either of steel or Glass-FRP. Establishing the effect of bar stiffness, surface texture and pattern and passive confinement on the characteristic average bond-slip relationship was a principal dimension of the investigation. The nominal ratio E_S/E_G of the elastic moduli of the two types of bars tested was 4.88; in all specimens considered, a constant C/D_b ratio of about 3.0 was used aiming to encourage a mixed splitting/pullout failure (C is the concrete cover and D_b the bar diameter). (Note that the value $C/D_b=2$ used by most design codes is intended to suppress a pure splitting failure) (ACI 318(2000), EC2). Passive confinement was provided by loose metal rings placed along the anchorage length; these are mobilized once the cover splitting cracks have propagated to the ring radius, producing a pseudo-yield plateau after attainment of peak strength in the bond-slip envelope. Using the rings was of interest in the study as a means of causing a controlled bond failure on the FRP bars, thereby generating an artificially ductile behavior for the FRP bar in tension while at the same time limiting the magnitude of tensile stress developing in that

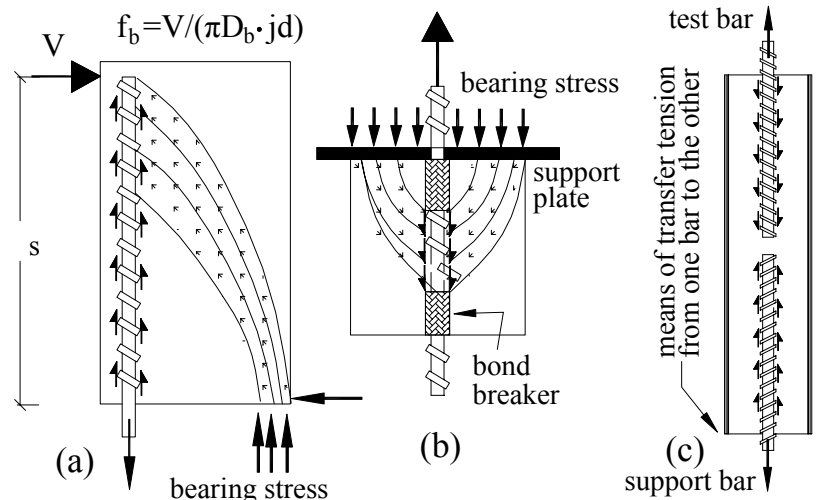


Fig. 3: Typical morphology of specimens for assessment of bond-slip law where concrete is partly stressed in compression ((a) & (b)) and setup of the Direct Tension Pullout Bond Test where the whole system is stressed in tension (c).

reinforcement type. (A motivating premise for this solution was to attempt to generate a ductile fuse for this brittle bar by managing bond, in the framework of capacity design). The length of embedment was over $14D_b$, representing *long* anchorage conditions (note that conventional short anchorage specimens usually have bonded lengths ranging between 3 and $6 D_b$. But in actual members, anchorage lengths in a well-detailed anchorage may exceed 30 times the bar diameter). Specimen dimensions were chosen so as to simulate realistic conditions for quantifying bond in a tension stress field. The behavior of the proposed test was compared with results of conventional cubic pullout specimens, beam-splice and beam-end tests demonstrating that the most adverse conditions for bond occur when the cover

concrete is under a direct tension stress field, yielding bond strengths that are substantially lower than values obtained by most established conventional bond tests.

2. MATERIALS AND EXPERIMENTAL PROCEDURE

Two groups of DTP - bond tests were examined with identical dimensions; the concrete cylinder length and diameter were 450mm and 100mm respectively. The first group comprised 21 concrete cylinders with a concentric test GFRP bar having diameter $D_{b,G}=12.7$ mm and a clear cover of 44 mm ($=3.44D_{b,G}$) anchored end to end with a support steel bar $D_{b,S}=14$ mm without splicing. The nominal mechanical properties of the composite rod were $f_u=740$ MPa and $E_G=40.8$ GPa (commercially available product, manufactured by Hughes Brothers). The embedment length of the GFRP bar was $L_{b,G}=250$ mm ($\cong 20 \cdot D_{b,G}$) whereas for the steel bar $L_{b,S}=200$ mm ($\cong 14 \cdot D_{b,S}$). Normal weight concrete was used with a 28-day cylinder strength of 27.4MPa (at the period of testing strength was increased to 33MPa – these are average values obtained by testing three 150×300mm cylinder specimens). The second group comprised 9 specimens, having an S500 steel test bar with a measured yield stress of $f_y=550$ MPa, $D_{b,S}=14$ mm (clear cover of 43mm, i.e. $C/D_{b,S}$ ratio of 3.0), embedded over a length $L_{b,S}=200$ mm ($\cong 14 \cdot D_{b,S}$) and having a 28-day concrete compressive strength of 21MPa (at the time of testing, 2½ years after casting and curing under laboratory conditions, strength had increased to 31.2MPa, at the same value as in the first group).

In conducting the DTP bond experiment, both the test and the support bar were pulled in tension simultaneously; force transfer was achieved from one anchorage to the next through the core concrete in the central portion of the specimen, but also through an external jacket of longitudinally bonded GFRP or CFRP wrap comprising two layers. The support region (anchorage zone of the support bar) was confined by a layer of externally bonded GFRP jacket, which was glued with the primary strength direction oriented transversally to the longitudinal axis of the cylinder. Note that the transverse sheet was discontinued past the end point of the test bar anchorage, so the embedment length of the test bar was left entirely unconfined. The mechanical properties of the sheets were: for GFRP sheets, $E_{Gf} = 70$ GPa, $\varepsilon_{u,Gf} = 3.1\%$, $f_{u,G} = 2250$ MPa, and $t_{Gf} = 0.17$ mm, whereas for CFRP sheets, $E_{Cf} = 230$ GPa, $\varepsilon_{u,Cf} = 1.5\%$, $f_{u,Cf} = 3500$ MPa, and $t_{Cf} = 0.13$ mm (commercially available products, known as SIKAWrap). These precautions were essential in order to discourage other undesirable failure modes except bond failure along the test bar. In the case of the first group, a special gripping arrangement was used to hold on to the GFRP bar and secure development of the tensile strength of the bar without premature fracture at the gripping point. For this

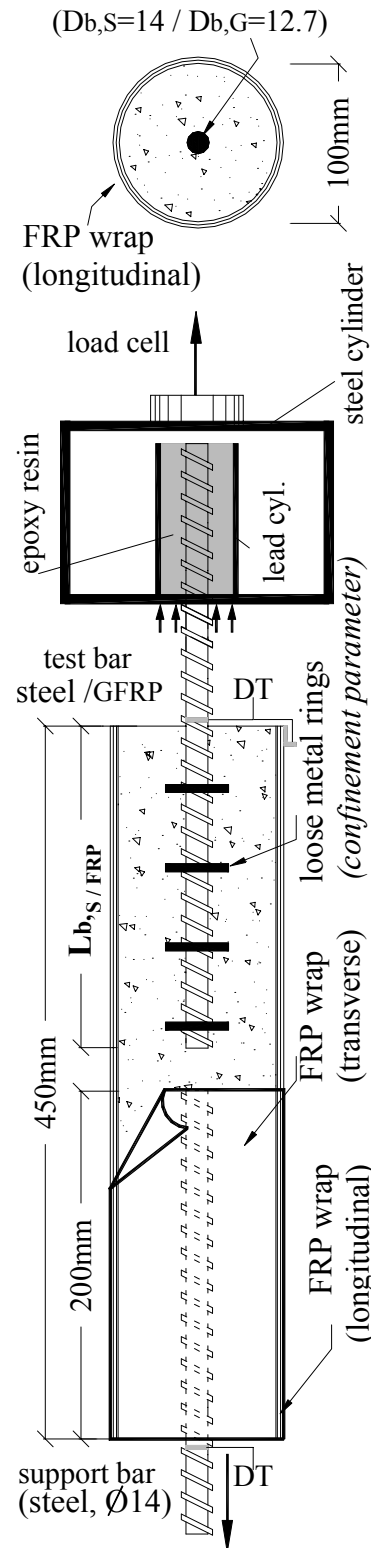


Fig. 4: Typical layout of the DTP- Bond Test

purpose, a thick lead hollow cylinder, filled with high strength epoxy (commercially known as SIKAdur 30) was sleeved on the GFRP bar end. The gripping arrangement involved using a metal plate under the sleeve. The plate was bolted on the loading actuator, thereby bearing on the lead tube (Fig. 4). Mechanical clamps (prestressing wedges) were used to grip the steel bars in tension.

Confining rings were placed loosely along the anchorage length of the test bar. The rings were fabricated from cold-formed steel wire having a cross-sectional diameter of 5mm. Two arrangements having either two or four rings were used in the two groups of specimens; three different ring diameters of 20mm, 30mm and 40mm were considered in the group of specimens with GFRP bars, whereas only 40mm diameter rings were used in specimens with steel test bars. In each case, specimens without rings were cast as controls. Table 1 outlines the details of the two DTP-BT specimen series as well as three additional sub-groups of specimens tested for comparison. These include (1) conventional concentric pullout tests of the same GFRP bars used in the DTP-BT specimen study; bars were embedded in 150mm long cubic prisms, (2) 1500mm long beam specimens with 150×250mm cross-section, reinforced with a single layer of two pairs of GFRP bars lap-spliced in contact in the constant moment region of the beam-span, which was tested monotonically to failure under four-point loading (Tastani and Pantazopoulou 2001); both groups were cast with the same batch of concrete as in the DTP-BT of GFRP bars specimens and (3) beam-end specimens with 250mm square cross section and 850mm in length, reinforced with a $\Phi 14$ steel bar pulled out monotonically to failure and concrete strength as that of the DTP-BT steel specimens (Tastani and Pantazopoulou 2002).

Table 1: Geometrical details of reinforced concrete bond specimens

Specimen Group	Dims (mm)	$f_{ck,28} / f_{ck,test}$ (MPa)	Test bar D_b (mm)	C / D_b	Anch Length L_b (mm)	Confinement: loose metal rings (D)	Total No.
DTP-BT Steel	450 / 100	21 / 31.20	Steel / 14	3.08	200 \cong 14 D_b	2D40/4D40/No Rings (NR)	9
DTP-BT GFRP	450 / 100	27.4 / 33	GFRP /12.7	3.44	250 \cong 20 D_b	2D20/2D30/2D40/4D20/4D30/4D40/NR	21
Short Cubic Pullout	150	27.4 / >33	GFRP /12.7	5.04	40 \cong 4 D_b	No confinement	3
Splice - Beams	1500 /250 /150	27.4 / 33	GFRP /12.7	2.36	550 \cong 43 D_b	2D40, 4D40, NR	3
Beam-End	850/250 /250	21 / 31.20	Steel / 14	1.43	415 \cong 30 D_b	No confinement	2

3. EXPERIMENTAL RESULTS

The two DTP-BT series were loaded monotonically to failure and the average bond strength values were calculated assuming a uniform distribution along the anchorage length L_b (mm):

$$f_b = \frac{P}{(\pi \cdot D_b \cdot L_b)} \quad (N.1)$$

where P (Nt) is the applied load and D_b (mm) the diameter of the test bar (equation N.1 also applies to the cubic specimens). To obtain slip measurements for both the test and the support bar, three displacement transducers (DT) were placed near the top and bottom faces of the cylinder (Fig. 4); lateral expansion of the concrete cylinder due to the bond (splitting) action of test bar (referred to as Poisson's Effect of *reinforced concrete*, Vecchio and DeRoo 1995)

was measured by two cross-diametric strain gages glued transversally to the longitudinal axis of the specimen at a distance of 100mm from the top face (pullout end).

3.1 Direct Tension Pullout Bond tests of GFRP bars

The DTP-BT with GFRP bars gave consistently bond strength of around 5MPa (Fig. 6). Specimens without rings failed after through splitting of the cover and a corresponding slip of the front end of the bar from the concrete cylinder, by as much as 10mm. The relative insensitivity of strength to the confining influence of the rings is attributed to the bar's surface texture (sand-coated without ribs, with a helical indentation of about 1mm in depth and 3mm in width). Thus, the bearing action of the "indentations" was marginal up to almost total cracking of the cover and substantial slip; the confining rings were activated at advanced stages of slip, producing a pseudo-yield plateau and delayed softening in the post-peak segment of the average bond-slip relationship. Mode of failure was markedly influenced by the layout, number and diameter of the rings. By increasing the number of the rings and/or their diameter, the bar-cylinder system toughness increased, with a corresponding increase in energy dissipation (Fig. 6). Bond values are compared with the respective data obtained from conventional pullout specimens in Fig. 6; the confining influence of that specimen's morphology tripled the bond capacity of the bar. The lowest bond strength values were obtained by the lap-splice beam tests; this result should be interpreted with caution, as the average bond stress from beam-lap splice tests is not directly comparable with the results of other test types. In the constant moment region bond reverses sign along the bar between successive cracks, the spacing of which is a function of effective bar stiffness or the so-called tension stiffening effect (Fig. 5). Thus, the local maximum value of bond may be several fold the average value, as illustrated in Fig. 5. In the test, with GFRP bars being much more flexible than conventional steel reinforcement, cracks were spaced rather narrowly, leading to

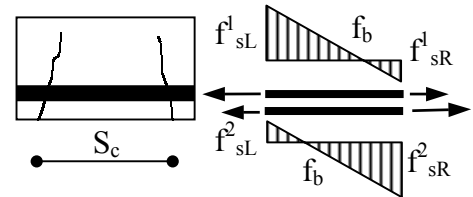


Fig. 5: Bond reversal between successive cracks

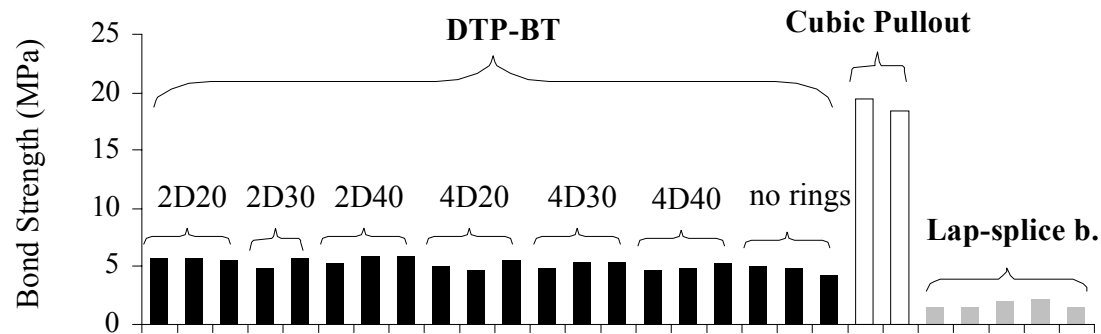


Fig. 6: Comparative values of Bond Strength obtained by three test setups

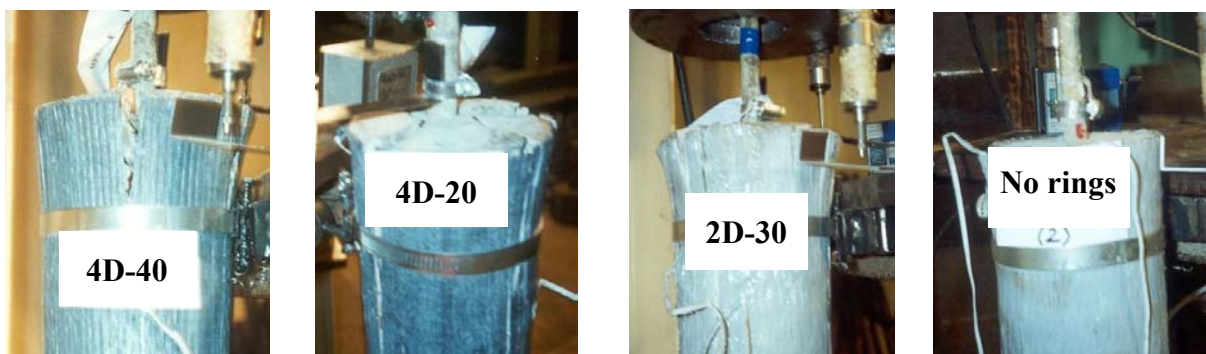


Fig. 7: Mode of failure for different arrangements of rings in DTP-BT of GFRP bars

excessively low average bond stresses (Tastani and Pantazopoulou 2001).

3.2 Direct Tension Pullout Bond tests of Steel bars

This series of tests were done under displacement control (0.02mm/sec) aiming to capture the descending branch of the bond – slip response envelope. The results are depicted in Fig. 8a and 9a, where index **0D** refers to specimens without rings, whereas **2D40** and **4D40** refer to specimens with two and four rings, 40mm in diameter, placed along the embedded length of the steel bar. Specimens 0D and 2D40 demonstrated identical responses up to peak load, but different energy dissipation in the post-peak branch; this implies that the corresponding rings were activated after significant slip had occurred (at a slip of about 0.5D_b, clearly less than the rib spacing). Specimens 4D40 showed a 30% increase of bond strength and stiffness due to the improved and more uniform confinement provided by the four rings placed along the anchorage. As in first group of specimens, failure was marked by splitting of the cover and slip of the test bar; with the addition of rings toughness increased marked by reduced steepness of the descending branch. Failure of specimens with rings occurred after thorough spalling of the cover at advanced stages of slip after separation of a concrete cone at the bar front and outwards movement of the upper rings (Fig. 8a, 9b,c). Average bond stress values obtained through the DTP-BT were consistently lower than those measured by beam-end specimens (Fig. 9a) highlighting that in every case (conventional pullout and beam-end tests) the proposed test gives a lower bound bond strength.

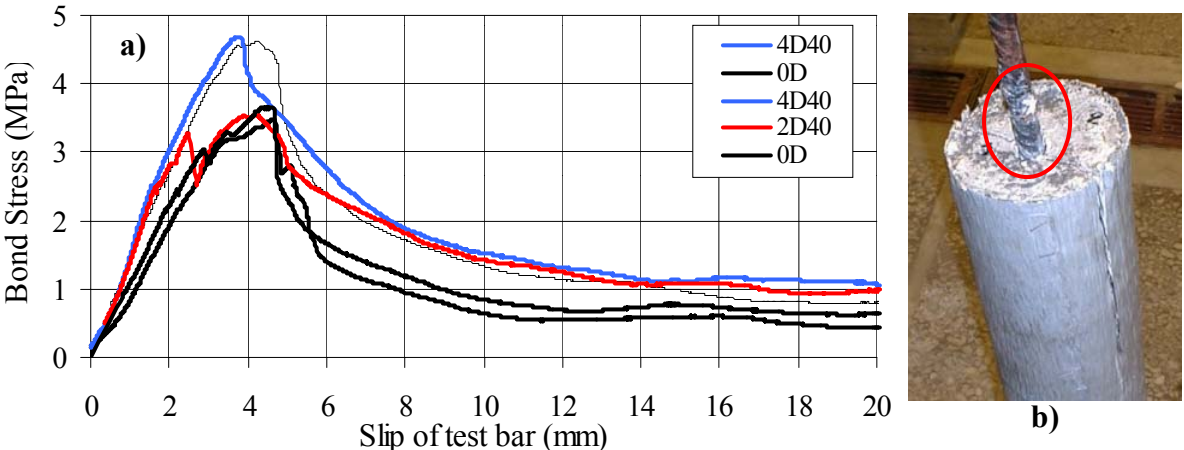


Fig. 8: a) Bond – Slip curves of DTP-BT of Steel bars with different arrangements of loose metal rings along the anchorage and b) mode of failure of a specimen without rings (0D)

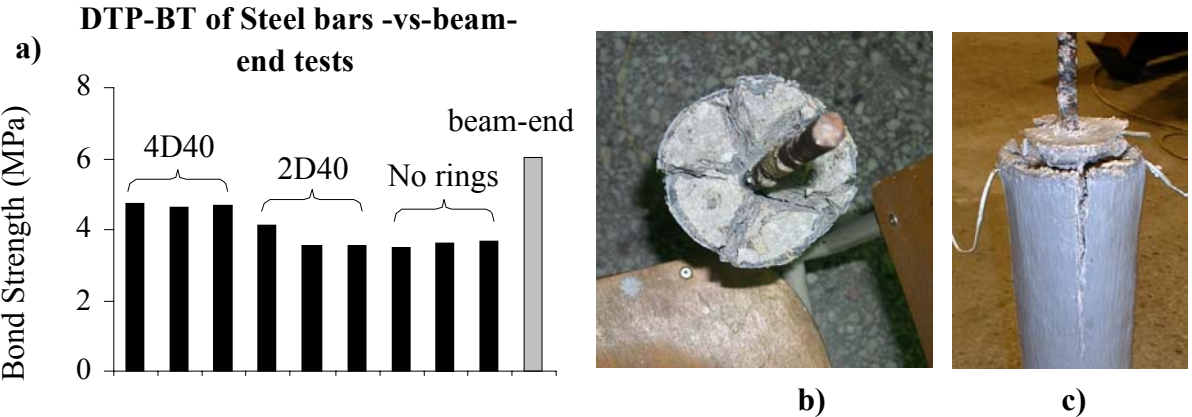


Fig. 9: a) Comparative values of Bond Strength obtained by two test setups and b & c) mode of failure of a specimen with 4 rings of 40mm in diameter (4D40)

4. CONCLUSIONS

This paper presents results of an experimental investigation of the performance of an alternative bond test known as DTP-BT (direct tension pullout bond test) designed to quantify the lower bound bond properties of steel and GFRP bars embedded in normal strength concrete. In designing the test setup objective was to simulate the stress field that develops in the concrete surrounding the reinforcement in the tension zone of flexural elements. To achieve this objective it was necessary to alleviate the spurious compression stress fields that arise around the anchorage region of conventional pullout specimens thereby leading to unrealistic bond values. Experimental evaluation of the proposed test setup included testing over 30 DFP-BT specimens of medium strength concrete. Parameters of the experimental investigation were the reinforcement stiffness (both steel and GFRP bars were considered) as well as the availability of external confinement (loose metal rings of various diameters were placed along the anchorage length, or alternatively, the anchorage zone was confined externally with FRP jackets). Conventional pullout and beam-splice tests were also done for comparison of results with those of the DTP-BT specimens. Through this investigation, it was demonstrated that the most adverse conditions for bond, which occur when the cover concrete is under a direct tension stress field, yield bond conditions that differ substantially from those obtained by most established conventional bond tests. For this reason the DTP-BT test is proposed as an alternative to the beam-end test in order to quantify bond for design purposes.

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