Influence of bond-slip on the behaviour of reinforced concrete beam to column joints

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ABSTRACT: The bond-slip correlation proposed by CEB is the most commonly adopted to predict slip displacements at the interface between steel bars and concrete. As known, the CEB model is based upon experimental results, obtained from pull-out tests performed on bars anchored by concrete for a limited length (usually 5 φ). In real beams the steel bar is usually bonded for a much longer length, and even in presence of concrete cracks, the maximum slip does not generally reach the values predicted by the CEB curve. An evidence of the above has been observed analysing experimental data, registered during a wide campaign for testing full scale r.c. beam to column joints, carried out by the Authors. Consequently, it has been calibrated a modified $\tau - s$ curve and an innovative test arrangement has been proposed, able to investigate bond-slip correlation for rebars in actual anchoring conditions.

In the paper they are illustrated some promising preliminary results, obtained with the proposed testing set up, confirming the experimental evidence about the significant modification of the bond-slip curve with respect to the CEB one.

1 INTRODUCTION

In the framework of a research programme aimed to investigate the cyclic behaviour of r.c. beam to columns joints (Bartelletti et al. 2004), a specific study has been addressed to the definition of an analytical procedure able to predict the experimental bending to rotation diagram of the beam, taking into account slip-bond effects.

In the first phase of this study, it has been investigated only the first loading cycle, leading to the formation of a plastic hinge in the beam, at the connection with the column.

It must be stressed that the theoretical analysis of r.c. elements in the cracked state, under the hypothesis of full bond condition, even considering naked steel bars, leads to a significant overestimation, up to 400% and more, of the stiffness of the actual r.c. elements, therefore the stiffness loss, caused by localised cracking and steel-concrete relative slip, cannot be disregarded.

In order to obtain a satisfactory fit of experimental moment to rotation curves, a suitable numerical iterative algorithm, described in the following, has been set-up. Starting from an appropriate bond-slip model, $\tau - s$, the algorithm allows to localise the cracks in the beam as well as to calculate stresses both in the concrete and in the rebars, during the whole loading process.

The correlation between bond, $\tau$, and slip, $s$, has been widely investigated in the past (e.g. Eligehausen et al. 1999). Results of these investigations are the background of the commonly adopted slip-bond CEB model (Bulletin, 2000), to which reference has been made at the beginning of the present research in the implementation of the algorithm.

Actually, numerical results derived using the CEB model do not fit the experimental ones. The discrepancies can be mainly ascribed to the different bond conditions of the rebar in the standard pull-out test or in the beam-test, rather than in the actual concrete beam, where the rebar itself extends for a sufficient length to develop full anchorage, allowing for much lower slips than those foreseen by the CEB model.

The numerical algorithm has so been parametrically calibrated, varying the $\tau - s$ model, in such a way to achieve an acceptable fit of the experimental bending to rotation diagrams.

These results shifted the attention of the Authors to the study of an improved test set up, allowing for more accurate measurement of the bond stresses in a fully anchored rebar, better simulating its actual restraint conditions.
In the paper the proposed test set up and some preliminary promising results are illustrated.

2 R.C. JOINTS BEHAVIOUR

2.1 The experimental campaign

The experimental campaign (Bartelletti et al. 2004) on 22 full scale r.c. joints was carried out at the Department of Structural Engineering of the University of Pisa in 2003–04.

The main scope of the research was the investigation of the influences of concrete class and of reinforcement detailing in seismic behaviour of beam to column joints, designed according to EC8. The results analysed in the present paper refer to the 11 specimens prepared with concrete class C50/60.

During each test, performed according to the typical test arrangement illustrated in figure 1, beside the measurements of loads and displacements of end sections, they were also registered the relative beam to column rotations through displacement transducers, placed at the elements’ intersections.

The first cycle of the loading process consisted in four loading-unloading steps, ending with the formation of plastic hinges in the beams, both for positive and negative bending moments. The subsequent cycles were obtained iterating the first one and increasing progressively the displacements of the beams’ end sections.

2.2 The analytical model

Slip-bond analytical model, currently adopted in literature, is derived considering equilibrium and compatibility conditions of a r.c. infinitesimal cylindrical tie of length $dx$, limited on one side by a crack and formed by a rebar and the surrounding portion of concrete ($A_c$) (see fig. 2).

The equation governing the global equilibrium of the tie, at the crack level is

$$ F = F_s + F_c, \quad (1) $$

being $F$ the total tensile force applied to the tie and $F_s$ and $F_c$ the quotas of $F$, acting on steel and on concrete, respectively.

Differentiating, and assuming $A_c$ to be constant, equation (1) gives

$$ dF = dF_s + dF_c = d\sigma_s \cdot \frac{\pi \phi}{4} + A_c \cdot d\sigma_c = 0 \quad (2) $$

$$ d\sigma_s = -\rho \cdot d\sigma_c \quad (3) $$

where $\rho$ is the reinforcement ratio, referred to the concrete area $A_c$.

Said $\tau$ the bond stress, function of the slip $s$, local equilibrium of the rebar over the length $dx$ gives

$$ d\sigma_s \cdot \frac{\pi \phi}{4} = \pi \cdot \phi \cdot \tau(s) \cdot dx, \quad (4) $$

and the compatibility condition

$$ (\varepsilon_s - \varepsilon_c) \cdot dx = dx, \quad (5) $$

from which

$$ \frac{d}{dx} s(x) = \varepsilon_s - \varepsilon_c. \quad (6) $$

Combining (2), (4) and (6), the following non linear differential equation is obtained

$$ \frac{d^2}{dx^2} \tau = \frac{4\pi(s)}{\phi} \left( \frac{d}{d\sigma_s} \varepsilon_s + \rho \frac{d}{d\sigma_c} \varepsilon_c \right), \quad (7) $$

which can be solved numerically, once input the $\sigma - \varepsilon$ relationships for both steel and tensile branch of concrete, as well as the $\tau - s$ law.
2.3 Constitutive relationships

The constitutive laws for concrete under tensile stresses and for steel were modelled by the Ramberg-Osgood formulations

\[ \varepsilon_c(\sigma) = \frac{\sigma}{E_c} + \frac{\sigma}{E_c} f_{\text{cr}}^{n-1} ; \quad \varepsilon_s(\sigma) = \frac{\sigma}{E_s} + \frac{\sigma}{E_s} f_{\text{y}}^{n-1} , \]

setting \( a \) and \( n \) to fit the experimental \( \sigma - \varepsilon \) diagrams.

Concrete ultimate strain was set as \( \varepsilon_{\text{cu}} = 0.115\% \).

As said, in the first elaboration, it was adopted the slip-bond law proposed by CEB for concrete in poor bond conditions, as illustrated in figure 3. More details can be found in Beconcini et al. 2007.

2.4 Numerical algorithm

Assuming that effective area of concrete increases from zero to \( A_c \), according to an exponential law, within a distance from the crack equal to the distance between two adjacent bars, solution of equation (7) can be implemented via finite differences method.

The process starts assigning the initial slip \( s_0 \) and its first order derivate \( s'_0 \) at the first crack, localised at the beam-column intersection. In this section, where \( \varepsilon_{\text{e0}} = 0 \), the value of \( s'_0 \) is linked to the steel strain \( \varepsilon_{\text{s0}} \) through equation (6). The value of \( s_0 \) can be determined as a function of the strain \( \varepsilon_{\text{a0}} \). A valid solution is achieved by a trail and error iterative procedure, when at the distance \( L_a \) from the crack, where \( s = 0 \), the condition \( \varepsilon_c = \varepsilon_s \) is satisfied. The distance \( L_a \) is the anchorage length, and its value increases, together with the concrete tensile stress, accordingly to the strains in the rebar \( \varepsilon_{\text{s0}} \).

The limit condition is achieved as soon as the tensile stress in the concrete reaches its ultimate value, when a second crack opens at a distance \( L_f \) from the first one (see fig. 4). Once the second crack is opened it is possible to determine the steel-concrete slip at each crack, applying backward the procedure illustrated above.

In this way it is possible to calculate, for each value of the bending moment, the relevant parameters, needed for deriving bending moment-rotation diagrams, to be compared with experimental ones.

2.5 Bending moment-rotation diagrams

In figure 5 the experimental bending moment-rotation diagram for one specimen is compared with the one obtained by the numerical algorithm described above, adopting the CEB slip-bond law.

In the figure, the curve labelled CEB1 presents an evident discontinuity, with a sudden rotation reduction occurring at the opening of the second crack in the beam, located at a distance of 125 mm from the column. This discontinuity is due to the concrete contraction at cracking: in fact, for rotation calculation, deformations are integrated over 90 mm, according to the transducers experimental set-up. Obviously, if the base length in the model would have been taken greater than 125 mm, in order to include the second crack, the diagram would have anyway presented a discontinuity (opposite side), as illustrated by the curve CEB2. There is no experimental evidence of such discontinuities; furthermore diagrams thus obtained (CEB1 and CEB2), closer to the experimental ones than that obtained under full bond hypothesis, still overestimate the element stiffness, in particular for higher values of bending moment.

Calculated slip values are much lower than those associated with softening branch of CEB model, so that it seems practically impossible to reach the ultimate limit state for bond, even at yielding of rebars.

These results ask for an improved bond model, capable to fit more accurately the experimental curves. To this aim a parametrical study has been performed, obtaining the \( \tau - s \) law shown in figure 6, which leads to a theoretical bending moment-rotations diagram,
3 EXPERIMENTAL EVALUATION OF THE BOND-SLIP RELATION

The relevant differences between the proposed bond-slip law and the CEB model put in evidence the need of further experimental investigation of the problem. In pull-out tests, even if modified to limit the disturb due to local compressive stresses in concrete (Tastani & Pantazopoulou, 2002), the rebar is bonded for a limited length (usually 5 $\phi$). This kind of test, in Authors' opinion, does not reproduce the actual condition of a rebar embedded in a r.c. beam, which is usually fully anchored at its ends. Starting from this remark, it has been studied an original test arrangement, suitable for the investigation of bond-slip behaviour of fully anchored rebars.

The specimen, to be tested in tension, consists of a ribbed steel bar, whose central part is embedded in a concrete cylinder, leaving the bar's ends free for the clamping in the testing machine.

Before concreting, the bar is instrumented with a considerable number of strain gauges, appropriately placed in order to register steel strain all along the embedded segment and out of it. To avoid the measure's alterations due to local effects, the strain gauges are placed into two opposite longitudinal grooves, obtained by milling the bar.

The total elongation of the concreted part and the local slip at its ends are measured through displacements transducers. The local strains of concrete are also measured by means of appropriate strain gauges, applied to the surface of the cylinder.

An example of such specimen is shown in figure 7. In this case the concrete 13,2 cm diameter cylinder is 100 cm in length, and the embedded $\phi$16 mm bar is 140 cm in length.

Global deformations are measured by four LVDTs A-type (fig. 7), while the relative slip is measured by a couple of LVDTs B-type (fig. 7).

The milled grooves are 2.5 mm deep, 3.3 mm wide and 1000 mm long. The strain gauges, whose measuring grid is 3 mm long, are spaced every 25 mm, and cover all the grooved segment.

Two couples of additional strain gauges are also placed on the naked ends of the bar immediately outside the concrete.
The tensile load is increased monotonically up to a stabilised cracking pattern, and further till the inelastic strain of the steel bar reaches a suitable value.

The knowledge of steel strains along the rebar allows to calculate, through equation (1) and constitutive relations (8), the stresses and strains in the concrete. From the equilibrium equation (4), applied to the generic 25 mm tie segment, it is possible to calculate the bond stresses \( \tau \) via numerical integration. Finally the slip \( s \) in each section can be calculated through the numerical integration of equation (6) and the \( \tau - s \) relationship consequently derived.

Before the occurrence of the first crack, the boundary condition on \( s \) is trivial, as \( s = 0 \) where \( \tau = 0 \).

Calculated \( \varepsilon_c \) strains can be checked with those measured by the strain gauges applied on the concrete surface.

After cracking the boundary condition is derived by the measurements of the B-type LVDT transducers, which give the relative slip at both the end sections of the cylinder. The crack opening can be checked against the total elongation of the concrete cylinder, measured by the A-type LVDT transducers.

The feasibility of the above mentioned specimen and the effectiveness of test procedure have been proved by a preliminary test carried on a simplified specimen, as described in the following.

The full specimen is currently under preparation and in figure 8 it is illustrated a detail of the milled groove, with strain gauges.

## 4 PRELIMINARY TEST RESULTS

A preliminary test has been carried out on a simplified specimen, having the overall geometry illustrated in figure 7, equipped with a lower number of strain gauges (spacing 50 mm) directly placed on the smooth surface of the ribbed steel bar, without any milling. A further simplification consists in the adoption of only one B-type LVDT.

The load was increased, in a first step, up to 83 kN; at that time the crack pattern was stabilised and five cracks opened; afterwards, the load was decreased down to 16 kN, increased again well beyond the yielding point of the bar. In figure 9 it is illustrated the specimen at the end of test.
5 CONCLUSIONS

Starting from the analytical modelling of r.c. beam to column joints, it emerged the need to further...
investigate the bond-slip correlation. Consequently an improved bond-slip model is being studied on the basis of a new proposed testing arrangement, able to better simulate the actual conditions of rebars in r.c. elements.

The proposed approach and test apparatus for the evaluation of the relevant mechanical parameters governing the phenomenon, appear to be suitable for the scope.

Even if the illustrated results are to be considered very preliminary and affected by some approximations, due to the reduced amount of employed instruments, they confirm that the maximum bond stress is associated with very small slip values, if compared with the CEB model, as well as the softening branch of the curve.

As said, in the near future it is planned to refine the test arrangement, using fully instrumented specimens, widening also the field of investigation, considering different concrete classes and bars’ diameters.

REFERENCES


Eligehausen, R. & Bigaj-van Vliet, A. 1999. Bond behaviour and models. Structural Concrete, the Textbook on Behaviour, Design and Performance (fib Bulletins 1, 2, 3).
