NON-LINEAR ANALYSES OF REINFORCED CONCRETE ELEMENTS WITH PRONOUNCED SLIPS OF LONGITUDINAL BARS

Franco BRAGA
Title Professor
University or Affiliation Dept. Of Structural Engineering, University "Sapienza" of Rome
Address via Eudossiana 18, 00184 Rome (Italy)
email address *franco.braga@uniroma1.it*

Rosario GIGLIOTTI
Title Assistant Professor
University or Affiliation Dept. Of Structural Engineering, University "Sapienza" of Rome
Address via Eudossiana 18, 00184 Rome (Italy)
email address *rosario.gigliotti@uniroma1.it*

Michelangelo LATERZA
Title Associate Professor
University or Affiliation Dept. Of Structural Engineering, University of Basilicata
Address C. da Macchia Romana, 85100 Potenza (Italy)
email address *michelangelo.laterza@unibas.it*

Michele D'AMATO
Title Research Fellow
University or Affiliation Dept. Of Structural Engineering, University of Basilicata
Address C. da Macchia Romana, 85100 Potenza (Italy)
*email address** *damato.mic@gmail.com*

Sashi KUNNATH
Title Professor
University or Affiliation Dept. Of Civil and Enviromental Engineering, University of California Davis
Address 95616 Davis (California)
email address *skkunnath@ucdavis.edu*

Abstract

The paper shows results of two non-linear cyclic analyses performed with OpenSees where slippage phenomenon of longitudinal bars is pronounced. Bond-slips have modeled by using the simplified model proposed by Braga et al. which assigns an equivalent stress-strain relationship to longitudinal steel accounting for both material elongation and relative slip. The model is also capable to take into account anchorages at bars ends (such as bends or hooks) and has been developed mainly for assessing older existing buildings where, because of the presence of reinforcing plain bars, bond-slips are particularly pronounced. Unlike many other refined models published in literature, the analytical formulation of the proposed model requires a minimum computational effort avoiding any nested iterations loop in the context of fiber model discretization of a section.

Keywords: Bond-slip, concrete elements, existing buildings, non-linear analyses, smooth bars, stress-strain relations.

1. Introduction

Slippage phenomenon may play a central role in the response of a reinforced concrete (RC) structure when it is subjected to lateral loads. It has been demonstrated by many experimental tests that bond-slip reduces the stiffness and hysteretic dissipation capacity of a structure and, therefore, makes inadequate the classical assumption of full-bond of longitudinal bars.

In older RC buildings significant slips verify because of plain bars applied and they are amplified by poor confining action due to absence of detailing rules within elements ends, by poor bond strength of concrete and by an insufficient lap splice of bars. Bond-slip also regards seismic response of concrete buildings reinforced with deformed bars because of micro-crushing of surrounding concrete owing to bar ribs.
This paper is aimed to show two analytical results of non-linear analyses performed on RC sub-structures when bond-slips are pronounced. The simplified model proposed by Braga et al. [1,2] has been applied for accounting bond-slips of longitudinal bars. It is capable of modeling straight and hooked bars and of defining an equivalent stress-strain relationship including steel elongation and relative slips with respect to the surrounding concrete.

2. Modified steel bar model accounting for bond-slips

The simplified model proposed by Braga et al. [1] has been developed on the following assumptions (Figure 1):

- bond-slip field u(x) is linear along the bar;
- bond-stress relationship is elastic-perfectly plastic;
- any anchorage at bar end (such as bend or hook) is described by a linear function of the displacement u_0 at end.

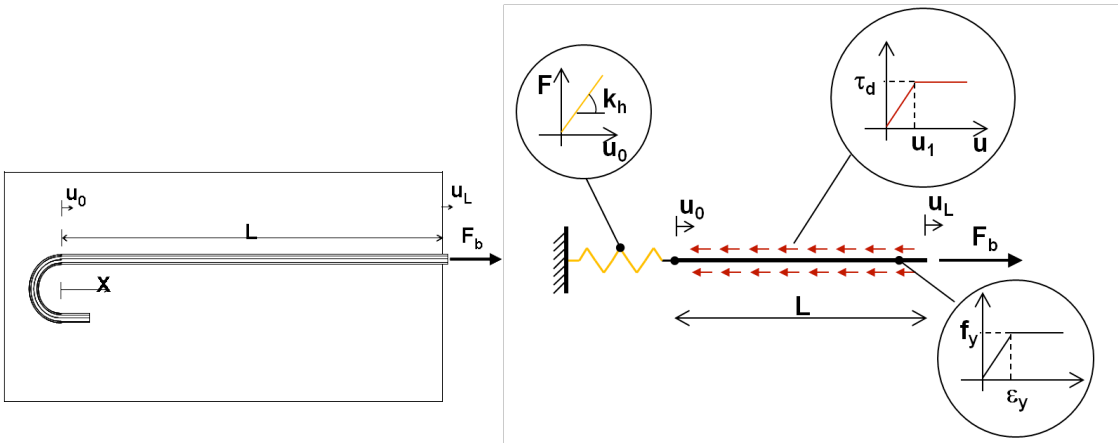

Figure 1. a) Longitudinal bar anchored in a concrete block and b) reference scheme [1]

The second assumption made becomes particularly appropriate in the case of smooth bars. For this kind of longitudinal reinforcements the bond strength peak sharply degrades and reaches a constant residual value owing to the friction between concrete and smooth bar. The constant value, moreover, is quite stable under cyclic loads [1]. As example, Figure 2 compares the assumed law with the one proposed by the ModelCode 90 [3].

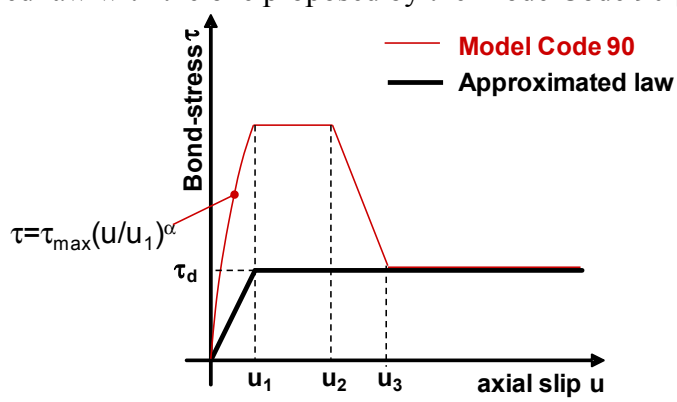

Figure 2. Bond stress –axial slip relationship proposed by ModelCode 90 [3].

It is demonstrated that the model uses a highly efficient approach to model bond-slip and requires a minimum computational effort without any nested iterations loop in the context of fiber model discretization of a section [2]. Analytical relationships for defining the curve are summarized in tabular form in [2].
Starting from the assumptions made the proposed model provides a non-linear monotonic tensile stress-slip relationship (σ-u_L) of a longitudinal bar embedded in a concrete block (Figure 1). The derived (σ-u_L) law accounts for both steel elongation and its relative slips with respect to concrete. Some examples of the (σ-u_L) relationship by varying the bar diameter are reported in (Figure 3).

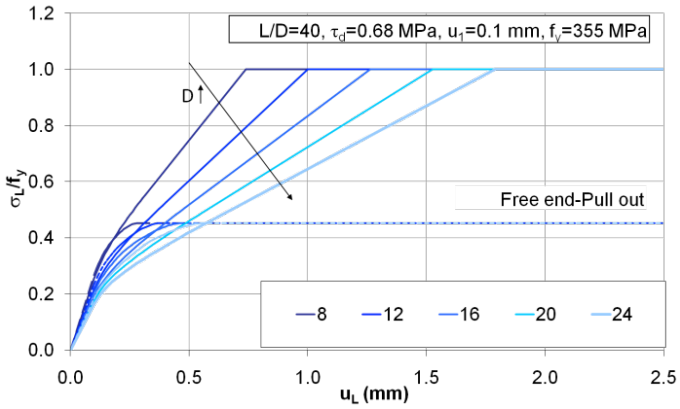

Figure 3. Different tensile stress-slip relationships obtained by varying the bar diameter

In a non-linear analysis program requiring the material relationship in the form of stress-strain law, the u_L can be intended as the integrated axial displacement of a steel fiber along the weighted length L_i of the elements ends, where L_i is the element part in the adopted integration scheme on which the response is constant. L_i may be intended as the plastic hinging region L_{pl} of the element. Starting from this assumption [2]:

$$\varepsilon = \frac{u_{L,tot}}{L_{pl}} \tag{1}$$

where $u_{L,tot}$ is the total relative axial displacement of a longitudinal bar calculated with the proposed model, and L_{pl} is the plastic hinge length.
The so-derived axial strain allows us to determine, starting from a (σ-u_L) law, a (σ-ε) law useful in a fiber-section state determination which is based on a section strain distribution.
The total displacement $u_{L,tot}$ is given by:

$$u_{L,tot} = u_{L,A} + u_{L,B} \tag{2}$$

where $u_{L,A}$ and $u_{L,B}$ are the relative axial displacement including the bond-slip related to adjacent concrete blocks (Figure 4).

Figure 5 reports different (σ-u_L) relationships obtained by varying the anchorage length in a concrete block (expressed as ratio L/D).
When in both concrete blocks an adequate anchorage length is available in the two schemes the steel yielding is reached and:

$$(\sigma, u_{L,A}) = (\sigma, u_{L,B}) = (\sigma, u_L) \tag{3}$$

Therefore, Eq. (2) becomes:

$$\left(\sigma, u_{L,tot}\right) = \left(\sigma, 2u_L\right) \tag{4}$$

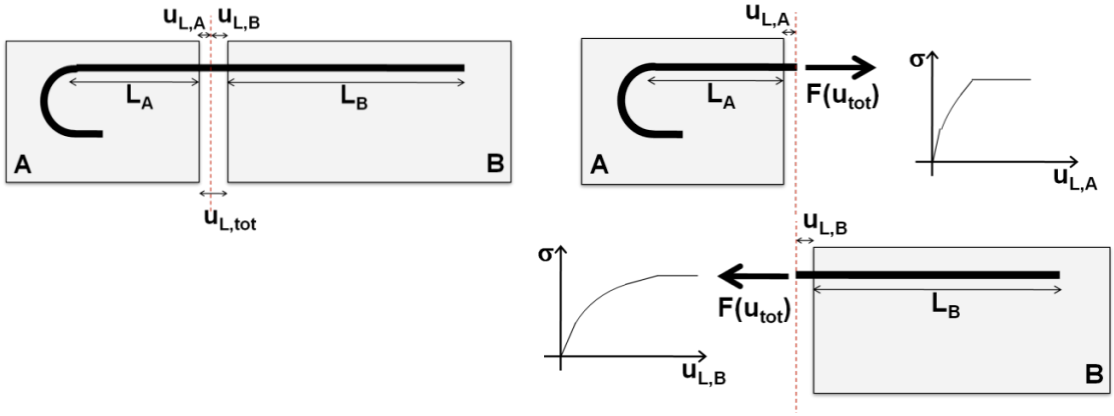

Figure 4. a) Total relative slip at the concrete crack and b) two anchorage schemes considered.

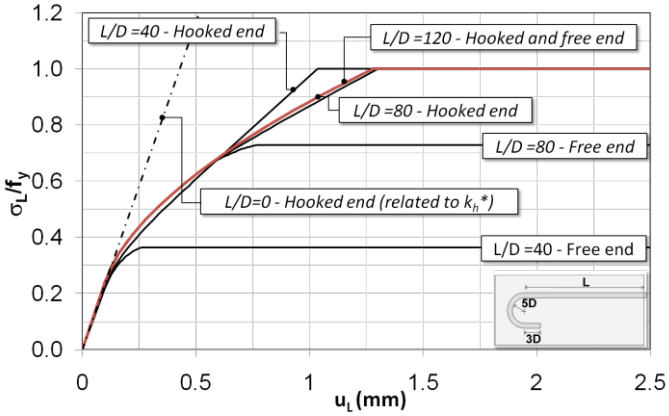

Figure 5. Tensile stress-slip relationships obtained by varying the ratio L/D.

As far as the modeling of the hooked end is concerned, the simplified model describes any anchorage as an elastic relationship referred to its initial section. Therefore, the stiffness of the hook is the only one parameter required in defining hooks or bends at the bar end. The authors propose to calculate the end stiffness k_h^* as the stiffness at the incipient pull-out condition [1].

In Figure 5 are reported some comparisons regarding hooked and straight bars having the same anchorage length ratio L/D. It is easy to note that the higher L/D ratio the closer the curves of a straight and hooked bar with the same length. Moreover, for ratios L/D higher than (L/D)' the both relationships are coincident.

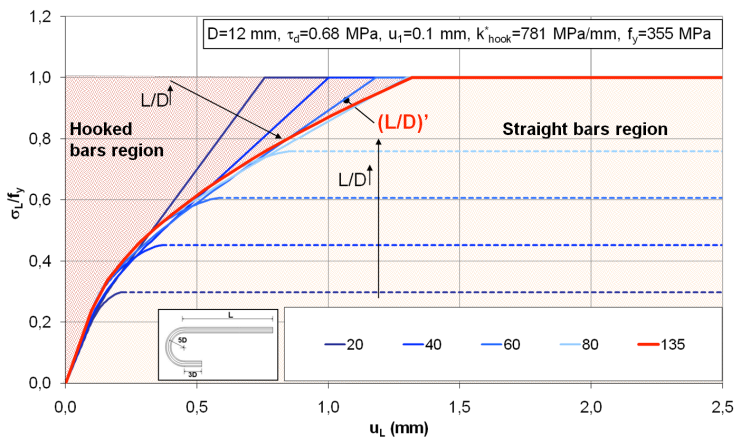

Figure 6. Comparisons between hooked and straight bars by varying the L/D ratio.

3. NUMERICAL SIMULATIONS

In performing non-linear analyses with OpenSees the non-linear (σ-ε) relationship has been applied by considering its equivalent relationship based on the energy principle. In particular, one can apply a bilinear or a trilinear equivalent relationship by using, for example, the uniaxial hysteretic material (*uniaxialMaterial Hysteretic* without any pinching factor (Figure 7).

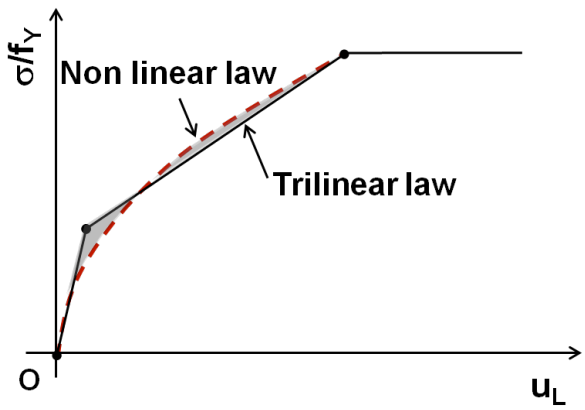

Figure 7. Example of trilinear law defined on the energy principle and assigned to longitudinal bars.

Hereafter, results regarding two non-linear analyses performed with OpenSees and comparisons with experimental results are shown. More in detail, simulations regard an internal RC beam-column joint reinforced with smooth bars [4] and a RC cantilever with deformed bars [5]. The confined concrete model proposed by Braga et al. (BGL model, [6]) has been used for the section core. The BGL model has been implemented into OpenSees with the *uniaxialMaterial* interface and named *ConfinedConcrete01* [7, 8].

3.1 Braga et al., Spec. C11 [4]

An internal beam-column joint (Spec. C11) reinforced with smooth bars was tested under a vertical load of 270 kN (axial load ratio of 16 %) without P-Δ effect. The specimen was designed only for vertical loads without any detailing rule for lateral forces in according to designing criteria adopted in Italy during '60s and '70s. The test was performed by applying a lateral displacement both in positive and negative direction at the top of the upper column. More details about the experimental program and results are reported in [4].

For numerical simulations beams and columns have been modeled with *BeamWithHinges* elements (Figure 8a). Detailed description of the analytical model is reported in [2]. Instead, in Figure 8b is reported the stress-strain relationship assigned to steel of longitudinal bars including material elongation and slippage phenomenon (red line). Slips reduce the stiffness and delay the yielding of longitudinal bars with respect to the full-bond design assumption (dashed line). Figure 8b also plots the equivalent trilinear relationship established with the energy principle assigned to steel fibers by using the trilinear hysteretic material (*uniaxialMaterial Hysteretic)* without any pinching factor. In according to the experimental measurements, the plastic hinge length for all elements has been assumed equal to h/3, where h is the depth of the section [2]. Rigid end offset at each element has been assigned for modeling the panel region.

In Figure 9 comparisons with experimental results are reported. Analytical simulations have been carried out by assuming the classical assumption of full-bond for longitudinal steel (Figure 9a) and by taking into account bond-slips with the proposed model (Figure 9b).

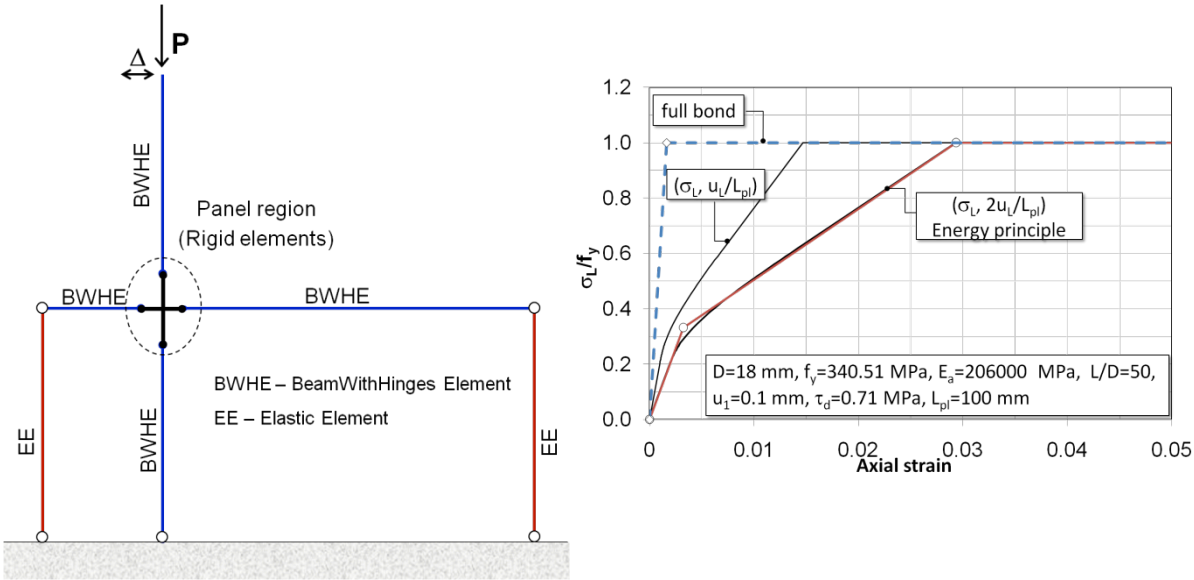

Figure 8. a) Analytical model adopted and b) stress-strain relationship assigned to longitudinal bars of column taking into account bond-slips.

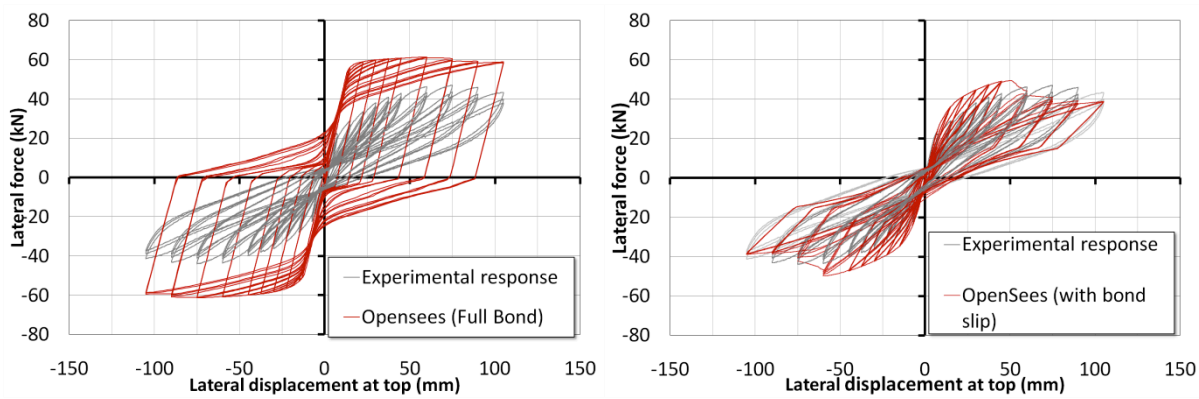

Figure 9. Comparisons with experimental results by considering a) full-bond for longitudinal bars or b) the proposed model accounting for bond-slips.

3.2 Saatcioglu and Ozcebe, Specimen U4 [5]

A cantilever was subjected to a lateral displacement at the top and to a constant axial load (axial load ratio of 18%, Figure 10). The cantilever was reinforced with deformed bars and failed in flexure [5].

The examined cantilever has been modeled in OpenSees with a *BeamWithHinges* element whose hinge length L_p is assumed equal to the section depth h of the column. Non-linear analyses take into account P-Δ effect by means of P-Delta Coordinate Transformation (*geomTransf PDelta*) [7].

In Figure 11a the confined concrete law calculated with the BGL model [6] and assigned to the section core is reported. Whereas, in Figure 11b the stress-strain relationship obtained with the proposed model for accounting the bond-slips is plotted. In the analyses the *Steel02* material is applied to reproduce the stress-strain for steel obtained.

In Figure 12 comparisons between experimental and analytical responses are depicted. Figure 12a shows the concrete relationship of the cover and of the section core. Stress-strain relationship for longitudinal bars is shown in Figure 12b where is also reported the steel material constitute law (blue dashed curve). An equivalent stress-strain relationship by using the *Steel02* material is applied in this analysis without the Bauschinger effect.

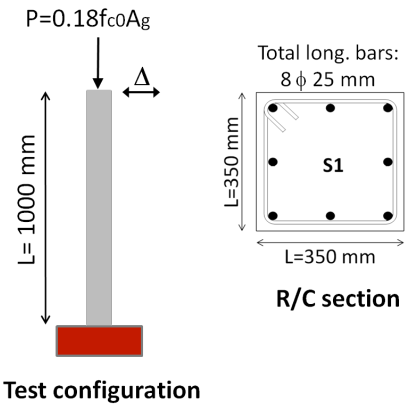

Figure 10. Cantilever model considered.

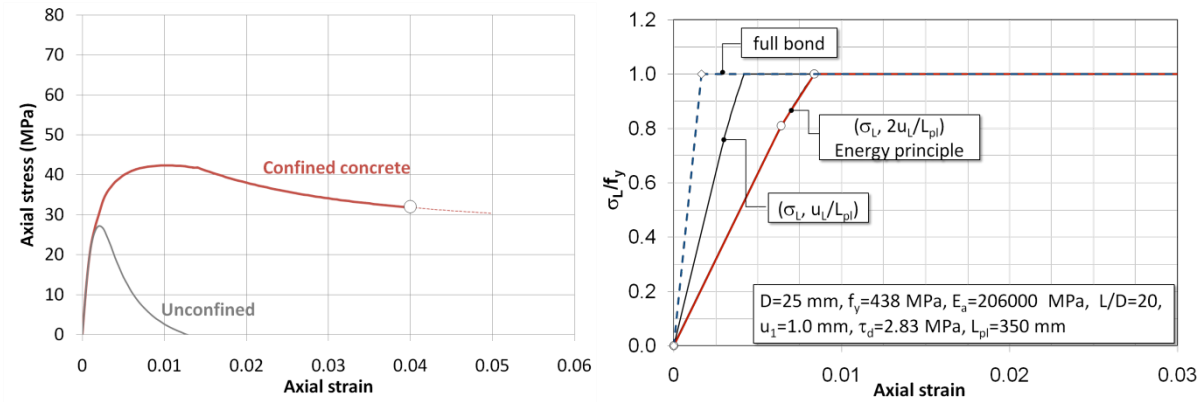

Figure 11. a) Confined concrete law obtained with the BGL and b) stress-strain relationship for longitudinal steel including bond-slip.

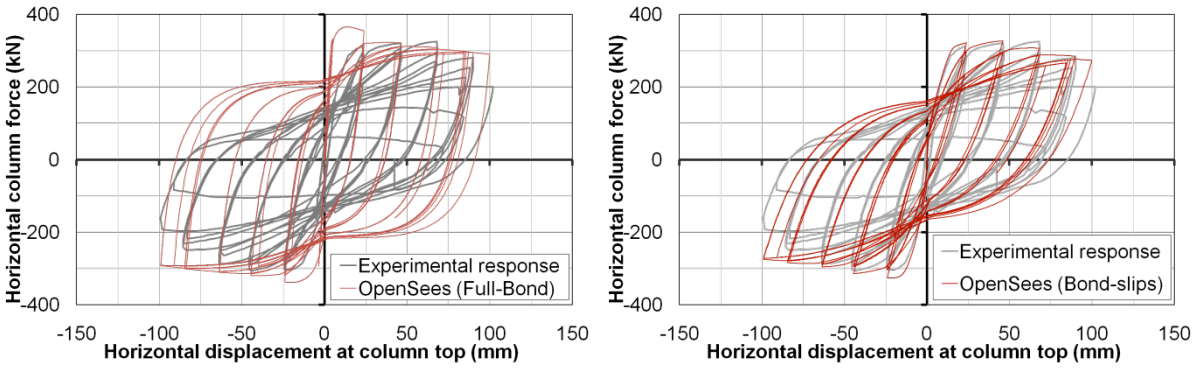

Figure 12. Comparisons with experimental tests by considering a) full-bond for longitudinal bars or b) the proposed model accounting for bond-slips.

4. Conclusions

The simplified model proposed by Braga et al. [1, 2] has been applied for simulating slippages between longitudinal bars and surrounding concrete. The model has been developed mainly for assessing RC existing structures where smooth bars have been usually applied and, unlike many other refined models published in literature, it does not require any nested iterations loops. With a minimum computational effort the model furnishes an equivalent steel stress-strain relationship accounting for material elongation and relative displacement between the longitudinal bar and concrete.

It is easy to recognize that the full-bond assumption implies fuller cycles with an overestimation of stiffness, resistance and, therefore, of energy dissipated under lateral loads.

The two comparisons carried out show a good agreement with the experimental results especially when system deformations become significant and the bars slippages dominate the global response either with plain bars or with deformed bars.

5. References

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