CONCRETE-STEEL BOND CHARACTERIZATION OF RC STRUCTURAL ELEMENTS BUILT WITH SMOOTH PLAIN REINFORCEMENT BARS

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Abstract
Poor bond conditions often lead to damage and ultimately to collapse of reinforced concrete structures under seismic loading. Reinforced concrete elements built with smooth plain reinforcement bars are particularly sensitive to the effects of bond degradation. With the objective of evaluating the bond-slip influence in the dynamic response of RC frames, representative of existing structures built in Europe in the 50's~70's with smooth plain reinforcement bars, a series of numerical analysis were performed. A simplified numerical model was developed to account for the effects of bond-slip. The proposed model was calibrated with the results of PsD tests on a full-scale structure.

1. Introduction

Observation on the performance of existing reinforced concrete (RC) structures during recent earthquakes all over the world, and particularly in Southern European countries, confirm their high vulnerability to seismic loads. Since they are the most common type of construction, RC buildings constitute an important source of risk for the society and can cause enormous economic losses and a large number of casualties in future events. The damage and collapse of RC buildings under earthquakes are often associated to poor concrete-steel reinforcement bond conditions, namely to the bond-slip mechanism. RC elements built with smooth plain reinforcing bars are particularly sensitive to this mechanism. An important number of existing RC structures in Southern Europe were

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constructed in the 50's~70's using smooth plain reinforcement steel bars, with poor bond conditions. Therefore, the consideration and calibration of the bond-slip effect in the numerical models is vital, so that a more realistic description of the cyclic behaviour and the ultimate capacity of RC structures under seismic loading can be achieved.

2. Common causes of damage and collapse of RC structures under seismic loads

The most frequent causes of damage and collapse of RC structures due to earthquakes are usually associated to the following effects/mechanisms [1]: i) stirrups/hoops, confinement; ii) ductility; iii) poor bond; iv) anchorage and lap-splices; v) inadequate shear capacity and failure; vi) inadequate flexural capacity and failure; vii) inadequate shear strength of the joints; viii) influence of the infill masonry on the seismic response of structures; ix) vertical and horizontal irregularities; x) effect of higher modes; xi) strong-beam weak-column mechanism; and xii) structural deficiencies due to architectural requirements.

3. Concrete-steel bond

Bond between concrete and reinforcement steel bars plays a fundamental role in the response of RC elements by allowing the stress transfer from the steel bars to the surrounding concrete. Bond is developed by friction, wedging action of small-dislodged sand particles between the bar and the surrounding concrete, and with bearing stresses against the faces of ribs. It is important to realize that when a bar is tried to pull-out of the concrete it tends to push the surrounding concrete apart, developing the so-called circumferential stresses. If the area of concrete surrounding the bar is small, splitting is the common mode of failure [1].

Perfect bond is usually assumed in the analyses of reinforced concrete structures, implying full compatibility between concrete and reinforcement strains. However, this assumption is only valid for early loading stages and low strain levels. As the loads increases, cracking and breaking of bond unavoidably occurs and relative slip between the concrete and the reinforcing bars (bond-slip) takes place in the structural elements. Consequently, different strains are observed in the steel bars and in the surrounding concrete, and the stress distribution is affected in both materials [1].

Bond-slip effects are particularly significant in elements built with smooth plain reinforcing bars for cyclic loading induced, for example, by earthquakes. Under these circumstances, the concrete-steel bond can deteriorate even before the stress state has attained the steel yielding stress or the concrete strength [2]. The bond-slip of smooth plain round bars gains vast significance considering that an important number of existing reinforced concrete structures in Southern European countries were built in the 50’s~70’s using these type of reinforcement steel bars.

4. A simplified approach for the inclusion of bond-slip in the numerical models

According to several authors ([3,4] among others), the introduction of bond-slip of reinforcement bars in the numerical models proves to be a necessary enhancement towards a realistic description of the cyclic behaviour and the ultimate capacity of reinforced concrete structures. A simplified approach to consider the bond-slip effect in the numerical models of analysis consists in adjusting the steel reinforcement constitutive laws with a global slippage factor [1]. In the following is briefly described the simplified model proposed.

When perfect bond is assumed between concrete and steel reinforcement longitudinal bars, both concrete (*c*) and steel (*s*) fibbers located at the same depth *y* have the same strain (ε).

$$\varepsilon_s = \varepsilon_c = \varepsilon \qquad (1)$$

Since this assumption is no longer valid when bond-slip occurs (see Figure 1), a correction factor, *S* (see Equation 2), can be applied to the steel reinforcement constitutive law in order to account for the bond-slip effect [1]. Basically, the correction is carried out by purely adjusting the characteristics of the monotonic steel behaviour law, considering smaller steel strain for a certain level of concrete strain.

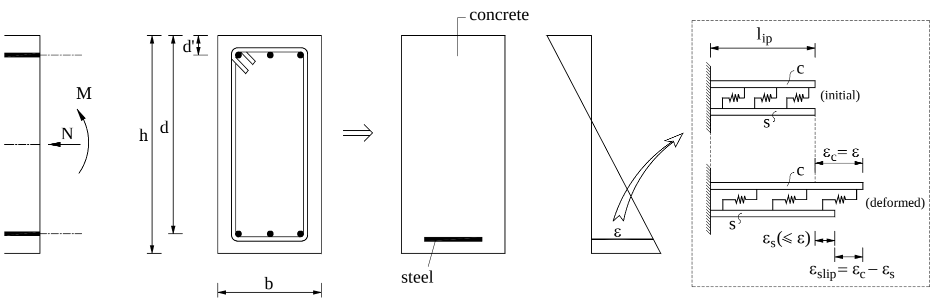

Figure 1. Bond-slip deformation between the constituent materials [1].

Assuming that steel hardening strain in not reached, the steel constitutive law can be assumed as a bi-linear law with an elastic perfect plastic behaviour, as represented in Figure 2.

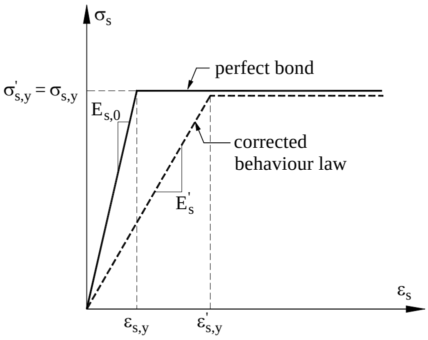

Figure 2. Steel reinforcement constitutive law (perfect bond and corrected) [1].

Equations 3 to 5 [1] express, respectively, the strain, stress and modulus of elasticity of the steel, considering the bond-slip effects. The slippage factor S assumes the value 1.0 when perfect bond between steel and concrete exists (see Equation 6).

$$S = \frac{\varepsilon_c}{\varepsilon_s} \qquad \varepsilon'_{s,y} = S \cdot \varepsilon_{s,y} \qquad \sigma'_{s,y} = \sigma_{s,y} \qquad E'_s = \frac{1}{S} \cdot E_{s,0} \qquad (2, 3, 4, 5)$$

$$\sigma_s(\varepsilon_s) = \begin{cases} \textit{if perfect bond} & \begin{cases} \varepsilon_s < \varepsilon_{s,y} \leftarrow \sigma_s(\varepsilon_s) = E_{s,0} \cdot \varepsilon_s \\ \varepsilon_s \geq \varepsilon_{s,y} \leftarrow \sigma_s(\varepsilon_s) = \sigma_{s,y} \end{cases} \\ \textit{if not (not yielding steel occurs)} & \leftarrow \sigma_s(\varepsilon_s) = \frac{1}{S} \cdot E_{s,o} \cdot \varepsilon_s \end{cases} \qquad (6)$$

5. Influence of bond-slip in the dynamic response of a RC frame: case study

A numerical analysis on a full-scale RC frame built with smooth plain reinforcement bars was performed with the objective of evaluating the influence of bond-slip in its cyclic response under simulated cyclic loads. The structure was built under the ICONS research programme [1] and was experimentally tested for several levels of seismic intensities. The available results of the test campaign were used to calibrate the numerical model proposed in this paper.

5.1 General description of the structure

The RC frame under study (see Figure 3) was built with smooth plain reinforcement bars and can be considered representative of the design and construction common practice until the late 1970's in Southern European countries, such as Portugal, Italy and Greece. The frame was designed to withstand vertical loads only. The reinforcement details were specified in accordance to the normative available and to the construction practice at that time. Thus, no specific seismic detailing provisions were considered, preferential

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inelastic dissipation mechanisms were not assumed and no specific ductility or strength provisions were provided [1].

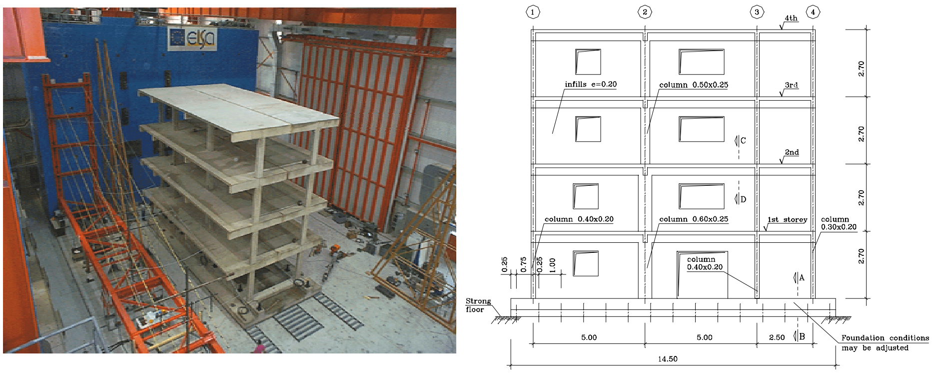

Figure 3. RC frame tested pseudo-dynamically [1].

It is a RC 4-storey frame with three bays: two of 5.0 m span and one of 2.5 m span. The inter-storey height is 2.7 m and a 0.15 m thick slab of 2.0 m on each side was cast together with the beams. Equal beams (geometry and reinforcement) were considered on all floors. All but the wider interior column have equal geometric characteristics along the height of the structure. Only this column is working in its stronger axis. Therefore, this column plays a dominant role in the structural response of the frame and is hereafter referred as 'strong-column'. The other columns are referred as 'slender-columns'. The strong-column is characterized by a rectangular cross-section with dimensions of 0.60 m × 0.25 m on the first and second storeys and 0.50 m × 0.25 m on the third and fourth storeys. All beams in the direction of loading are 250 mm wide and 500 mm deep, while transverse beams are 200 mm wide and 500 mm deep. The materials considered at the design phase were a normal weight low strength concrete, class C16/20 (according to EC2), and round smooth reinforcing steel of class Fe B22k (according to the Italian standards). The frame was built without masonry infill walls. Detailed information about the RC frame dimensions and characteristics, detailing, material properties, static and earthquake loads, and results of the test campaign, can be found in [1].

5.2 Numerical model

A non-linear numerical model of the structure was developed and calibrated using the non-linear analysis software VISUALANL [6,7,8]. The model was calibrated based on the available experimental results. All parameters which characterize the non-linear behaviour of the elements at section level were computed with the BIAX software [9]. Figure 4 presents the frame general geometry and the nomenclature of each structural element (beams and columns) in the numerical model. Details concerning the frame and geometric characteristics of the structural frames, material properties, static and seismic loadings considered in the analysis, can be found in [10].

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The VISUALANL software considers each structural element as being constituted by 3 sub-elements: one central sub-element with linear behaviour and two external sub-elements with non-linear behaviour (see schematic representation in Figure 5). The parameters which characterize the non-linear behaviour of the external sub-elements were computed by the fibber model software BIAX. The non-linear behaviour of RC elements under seismic loading is fundamentally controlled by flexure. In VISUALANL, the hysteretic behaviour of the elements is defined by an envelop monotonic curve, representative of the RC element non-linear behaviour, in terms of curvature-bending moment.

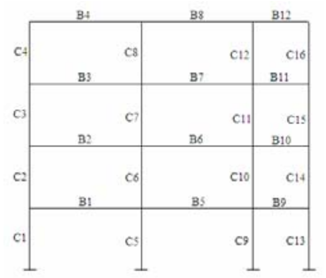

Figura 4. General geometry of the frame [10].

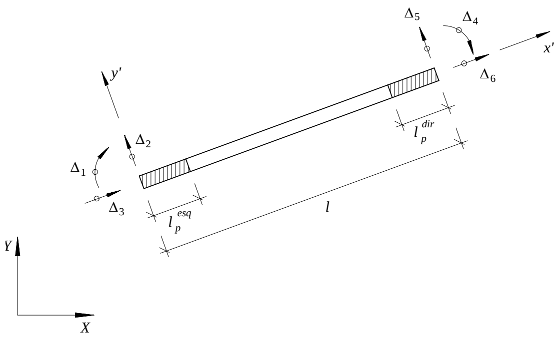

Figura 5. Structural element macro-model [6,7,8].

5.3 Bond-slip modelling

Bond-slip was modelled explicitly using a correction of the steel reinforcement constitutive law, as explained in Section 3. Several levels of slippage were considered by reducing the modulus of elasticity of the reinforcing steel in the constitutive law of each RC element (beams and columns). The corresponding slippage factor was calculated using Equation 5. Each element behaviour curve, in terms of bending moment-curvature relation, were computed by the BIAX software, considering and not considering the bond-slip mechanism. From the obtained curves, a trilinear curve as approximated for each structural element. As example, in Figure 6 is presented the behaviour curve of column C6 for various levels of slippage, and the curve adopted in the numerical analysis of the structure. Note that from slippage factor larger than 10, $S > 10$ (see Figure 6-a), the curves tend to converge for the same values.

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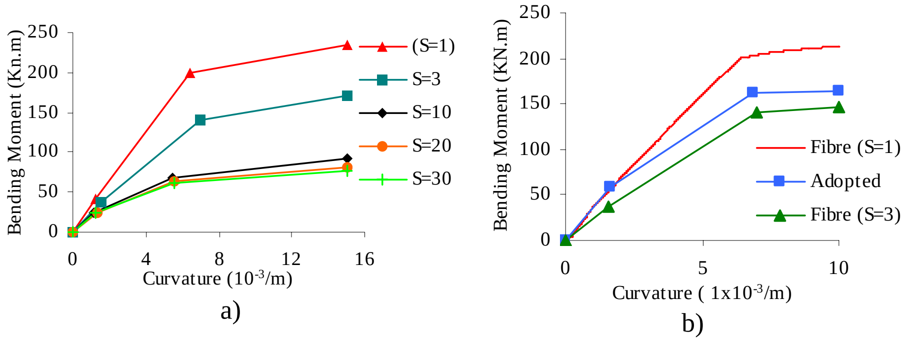

Figure 6. Monotonic behaviour curve of column C6: a) various levels of slippage; b) adopted curve for the analysis [10].

5.4 Bond-slip influence in the dynamic response of the RC frame

Intending to evaluate the influence of the bond-slip in the RC frame behaviour when subjected to seismic loading, a comparison was made between the response of the frame considering and not considering the bond-slip mechanism. The results in terms of shear-drift response are presented in Figure 7.

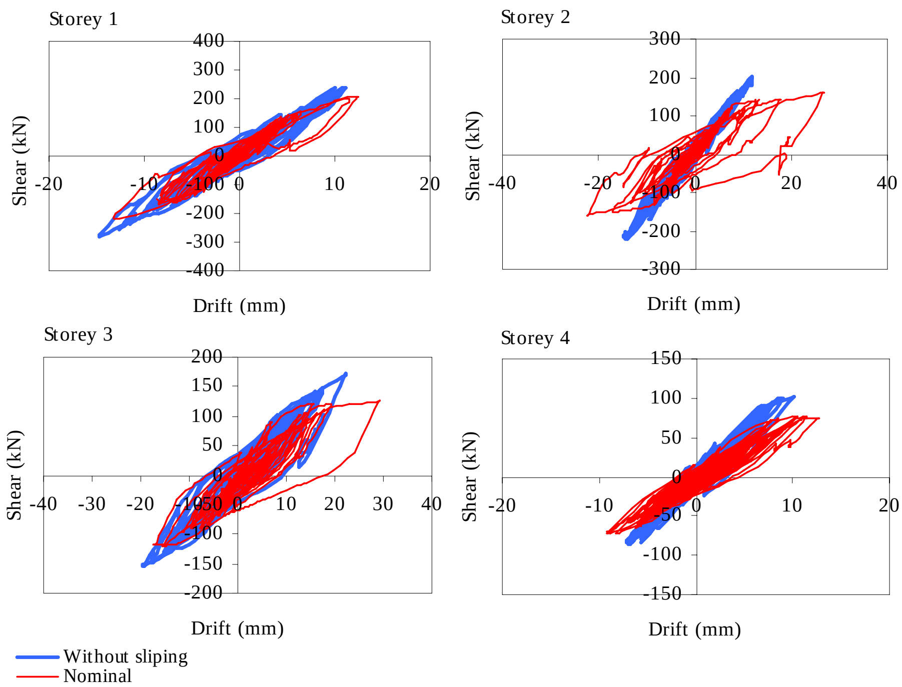

Figure 7. Storey shear-drift response considering and not considering the bond-slip mechanism [10].

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In the numerical analysis described in [1] concerning the behaviour of the frame under study, Varum [1] concluded that only with the inclusion of the bond-slip effect in the numerical models it was possible to well reproduce the experimental test results. Figure 8 presents a comparison made between the experimental results (see [1]) and the results from the numerical model, considering the bond-slip mechanism. The results are presented in terms of shear-drift response at storey levels.

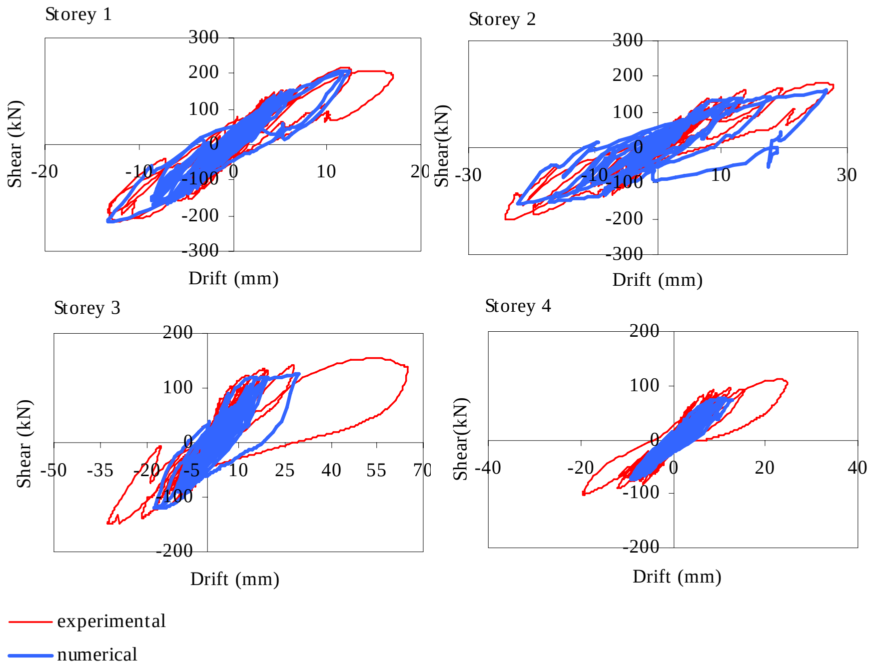

Figure 8. Comparison, in terms of storey shear-drift, for the experimental test results and the numerical results, considering the bond-slip mechanism [10].

5.5 Results analysis

Concerning the bond-slip influence in the dynamic response of the RC frame, presented in Figure 7, the following conclusions can be made:

- Storey 1 is the less sensitive to the bond-slip mechanism. The behaviour with and without considering the steel reinforcement bars slippage, is very similar.
- Storey 2 is the most sensitive to bond-slip. Including bond-slip in the numerical model leads to a significant increase of drift demands (150% maximum), comparing with the response without slippage.
- Storey 3 and Storey 4 are also vulnerable to the bond-slip effect. A 32% and 26% increasing of drift, respectively, is verified comparing with the response without slippage.

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Regarding the capability of the simplified numerical model to represent the pseudo-dynamic experimental results, on the full-scale structure, the analysis of Figure 8 allows concluding that the proposed model was able to capture the global response, not only in terms of maximum forces and deformations values, but also in terms of energy dissipation. The inclusion of bond-slip in the numerical model leads to a more realistic description of the frame cyclic behaviour.

6. Final conclusions

Considering bond-slip in the numerical modelling of RC structures subjected to seismic loads, leads to a more realistic description of their behaviour, as exemplified by the presented analysis performed on a full-scale RC structure.

A large test campaign on full-scale single structural elements is currently being prepared at the University of Aveiro. RC elements (beams, columns and beam-column joints) built with smooth plain bars will be tested under cyclic loading and the influence of bond-slip in the response will be thoroughly evaluated.

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