A Model to predict the non-linear shear and flexural behaviour of RC elements subjected to cyclic loading

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Abstract. The development and implementation of an integrated numerical model to predict the nonlinear response of RC structural elements, including nonlinear flexural and shear behaviour, is proposed and discussed. The presence of RC elements with dominant behaviour in shear is quite common in a significant number of existing and new buildings. Severe damages and/or collapse of buildings have been observed in recent earthquakes due to disregarding of the shear behaviour of these stocky elements. The main objective of the work proposed is the development of a numerical model able to simulate the cyclic behaviour of RC elements subjected to cyclic loads, as the induced by earthquakes. The proposed model would allow to better estimate the nonlinear response of RC buildings under severe ground motions, combining the nonlinear flexural behaviour with the nonlinear shear behaviour. The proposed model for nonlinear shear behaviour has been implemented in the computer program VisualANL and was calibrated with experimental results on full-scale tests on RC columns.

Introduction

From the observation of collapsed and severely damaged structures during recent earthquakes, it is clear the complex behaviour of RC buildings, and particularly under seismic actions. This fact underlines the need for refined numerical models that represent the behaviour of these structures at local and global levels. In this paper are presented and proposed a simplified non-linear shear model for RC elements, implemented in a structural analysis program (PORANL). In the analysis of RC structures, subjected to seismic actions, the use of non-linear models (monotonic behaviour laws combined with appropriate hysteretic rules) allows to a more rigorous representation of its response [1]. In fact, the original version of the PORANL program was able to represent the non-linear bending behaviour of RC elements (beams and columns). Each RC structural element is modelled by a macro-element defined as the association of three bar finite elements, two with non-linear behaviour at its extremities (plastic hinges), and a central element with linear behaviour, as represented in Figure 1 [2]. The non-linear behaviour of the plastic hinge sub-elements is controlled through a modified hysteretic procedure, based on the Takeda model, as illustrated in Figure 2. This model developed by Costa [3] represents the response of a RC cross-section to seismic actions and contemplates typical mechanical behaviour effects as stiffness and strength degradation, pinching, slipping, internal cycles, etc.

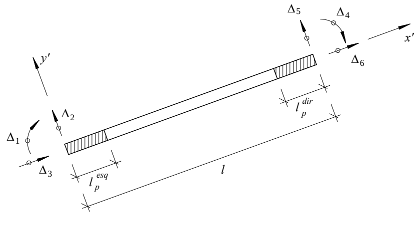


Figure 1: Frame macro-element

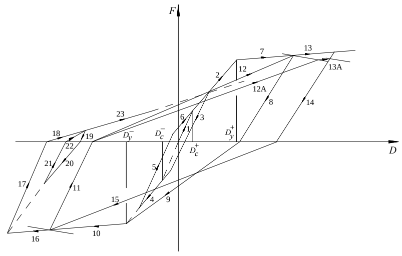


Figure 2: Hysteretic model for RC elements in bending

Behaviour of RC buildings under seismic loads

Structural deficiencies that influences the damages and failures of RC buildings under seismic action. The most common courses are associated with: i) stirrups/hoops, confinement and ductility; ii) bond, anchorage, lap-splices and bond splitting; iii) inadequate shear capacity and failure; iv) inadequate flexural capacity and failure; v) inadequate shear strength of the joints; vi) influence of infill masonry; vii) vertical and horizontal irregularities; viii) higher modes effect; ix) strong-beam weak-column mechanism, and, x) structural deficiencies due to architectural requirements [4]. However, it should be noted that normally structural damages and failures are associated to the combination of several of these factors. In this paper, is proposed a model for the simulation of the non-linear shear behaviour.

Inadequate shear behaviour. Typical design values of gravity and wind load normally results in design shear force in column significantly lower than the shear forces that could develop during seismic events. Therefore, shear limit states should be avoided in the seismic resistant structures. For this goal, the shear demand should be limited or shear capacity should be enhanced. Structural problems associated to insufficient shear strength or confinement is commonly more severe in corner columns, especially if for buildings with significant eccentricity between the centre of mass and the centre of resistance. When the load in the strong axis direction of the column, it often fails in shear (see example in Figure 3-a), Another common problem is artificially induced shorten a column by the presence of apertures, provoking stiffer, attracting much higher shear forces than were designed to carry. Short columns are vulnerable to shear failure as shown in Figure 3-b, where a column shear failure is induced by the partial infill walls is shown [4].

Figure 3: Columns shear failure during earthquakes

Model for shear behaviour of RC elements

Introduction. The seismic response of slender RC structural elements is dominated by flexure behaviour. But, when the slenderness drops to a certain level, the behaviour is controlled by shear. Shear behaviour is characterised by very low ductility and, generally, by poor performance under cyclic loading. In RC building structures, it is common to use RC walls to increase the global lateral stiffness of the structure, and therefore, controlling the lateral deformation demands induced by earthquakes. Current analysis programs support non-linear models only in bending. A new non-linear shear behaviour model was proposed and implemented in the PORANL computer program [2].

Proposed macro-model. The non-linear shear behaviour model was implemented in the PORANL program based on the formulation of the frame macro-model available for bending. Therefore, each RC structural element is modelled as the association of three bar finite elements, two with non-linear behaviour at its extremities, and a central element with linear behaviour, as represented in Figure 1. The non-linear monotonic shear behaviour curve of each sub-element is characterized through a tri-linear force-distortion relationship. The hysteretic rules are controlled by three additional parameters, namely: α - stiffness degradation; β - "pinching" effect; and, γ - strength degradation [5].

Hysteretic rules. In the shear model, the non-linear behaviour is characterized by hysteretic rules based on a modified Takeda's model [6], allowing to represent the response of RC elements to

cyclic loads, function of the material's behaviour (defined by the envelop behaviour curve and hysteretic parameters). The hysteretic rules are briefly exemplified in Figure 4.
The loading stiffness depends on the maximum force and displacement values reached in the previous cycle (F_{max} and d_{max}). The loading begin at the point corresponding to null-force (d_r) and its stiffness is defined by the Eq. 1:

$$K_r = \frac{F_{\max}}{d_{\max} - d_r} \qquad (1)$$

The unloading happens when a load inversion occurs. The unloading stiffness depends on the maximum displacement reached. Before the yielding-point has been reached, the unloading stiffness (K_d) will be equal to the initial stiffness (K_0). If the maximum displacement reached is larger than the yielding displacement, but smaller than d_{cr} (cracking displacement), the unloading stiffness (K_d) will depend on the parameter α, and on the maximum displacement reached in that cycle, defined by:

$$K_d = \frac{F_{cr} - \alpha \cdot F_y}{K_0 \cdot d_{cr} + \alpha \cdot F_y} \cdot K_0 \qquad (2)$$

If the maximum displacement reached is larger than d_{cr}, the unloading stiffness (K_d) will depend only on the parameter α. The unloading stiffness than is given by Eq. 3:

$$K_d = \frac{F_{cr} - \alpha \cdot F_y}{d_{cr} \cdot K_0 - \dfrac{\alpha \cdot F_y}{K_o}} \cdot K_0 \qquad (3)$$

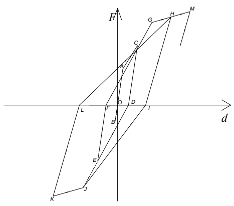


Figure 4: Hysteretic rules for the proposed shear model

The “pinching” effect is an important phenomenon in the cyclic behaviour of RC elements, particularly for elements were the shear behaviour is dominant. The pinching effect is represented dividing the reloading branch in sub-two branches with different stiffness (Figure 5). The pinching is controlled through the parameter β, and depends on the maximum displacement reached in previous cycles. The strength degradation, for repeated cycles of certain distortion amplitude, was implemented considering interaction between the degradation in shear in both directions.

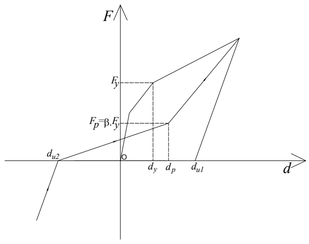


Figure 5: “Pinching” effect

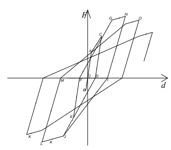


Figure 6: Strength degradation

Calibration of the proposed numerical model

The proposed macro-model to simulate the shear behaviour was verified using results obtained from a experimental campaign at the research project ICONS financed by EU. Two full-scale four-storeys, three-bays reinforced concrete frames (one as a bare frame and other as a infilled frame), representative of existing RC structures, were designed, constructed and tested [4]. The cross-sections' geometrical characteristics and the reinforcement detailing of the columns and beams as well as detailed results presentation and discussion of the experimental campaign can be found in the literature [4].

Calibration of the non-linear shear model. To illustrate the ability of the proposed shear model, it were simulated the response of the first storey strong column of the ICONS frame [4]. The studied column was exhaustively instrumented (see Figure 7 and 8-a). For the tests, were installed in the column, a set of 27 relative displacement transducers, located as represented in Figure 7, that allows to capture the column deformation (in bending and in shear) at three levels. To reproduce the measured deformations during the tests, it was build a simplified model for the column. The column was simulated with the following boundary conditions (Figure 8-b): a) displacements and rotations blocked at the base; b) compression axial force was applied, corresponding to the vertical loading; c) imposed lateral displacement (Figure 9) and rotation (Figure 10) at the top of the column, according to the measured values (local instrumentation) during the tests. For the imposed conditions, it was performed two series of analysis. First, it was considered only the bending behaviour in the response of the element. Secondly, it was considered the contribution of bending and shear stiffness.

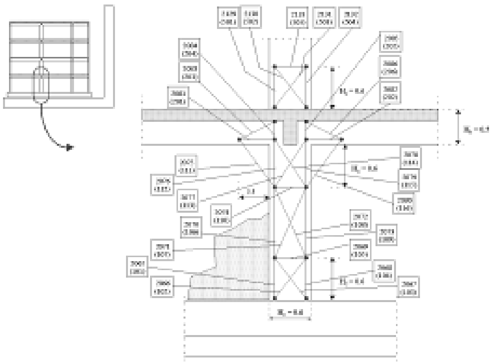


Figure 7: Instrumentation set-up

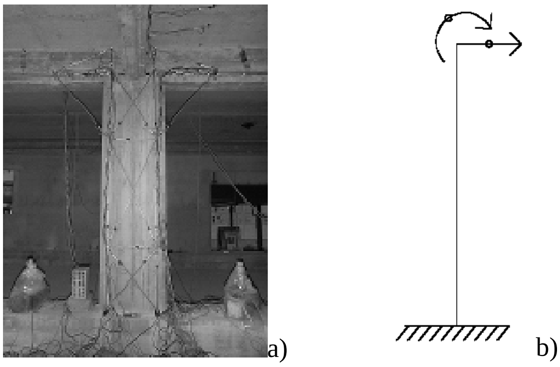


Figure 8: Studied column: a) instrumentation; b) structural model studied

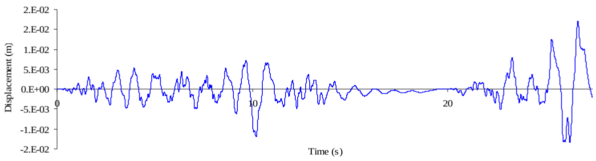


Figure 9: Horizontal displacement imposed at the top of the column

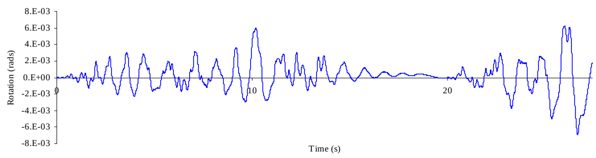


Figure 10: Rotations imposed at the top of the column

In the first analysis was modelled only the bending behaviour. In Figure 11 is presented the evolution of the shear force in the column (numerical estimation and experimental results). In Figure 12 are represented the global shear-drift curves of the column.

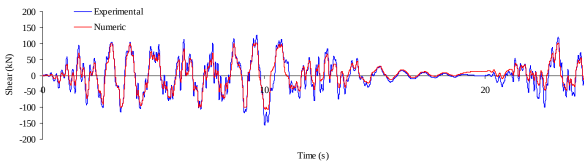


Figure 11: Column shear evolution considering only bending behaviour

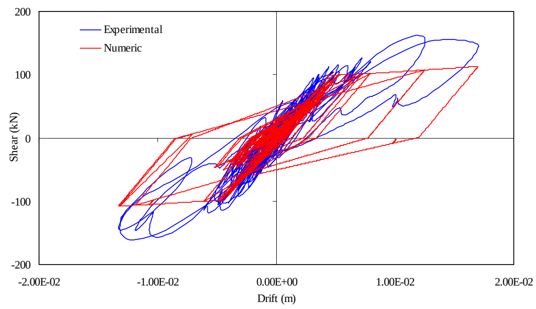
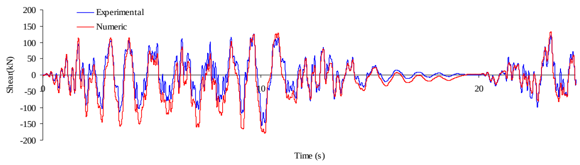


Figure 12: Shear-Top-Displacement, considering only bending behaviour

For the second analysis, it was modelled the response of the strong column to the imposed displacements and rotations at the top, considering the shear and bending stiffness contribution to the response. In Figure 13 is presented the evolution of the shear force in the column (numerical and experimental results). In Figure 14 are represented the global shear-drift curves.



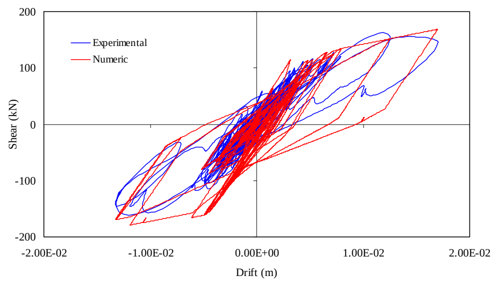


Figure 13: Column shear evolution in time considering bending and shear behaviour

Figure 14: Shear-top-displacement at top, considering bending and shear behaviour

From the obtained results, it can be concluded that for RC elements with considerable shear stiffness, the bending behaviour may not be able to accurately reproduce the response of these elements to cyclic loading, particularly for high demand levels. The numerical results presented illustrates that the combination of the bending with shear behaviour provides a better representation of the experimental results.

Final remarks

Structural analysis programs that include non-linear models are valuable tools in the analysis and verification of structural safety, giving the engineer capacity to representing more precisely the real behaviour of the RC structures. For design of new structures or for capacity assessment of existing ones, non-linear analyses allow for a better representation of the structural response under any loading condition, and particularly for earthquake loading. The proposed shear model was able to reproduce the experimental results, not only in terns of maximum peak values, but also in terms of the dissipated energy and hysteretic behaviour. However, a more exhaustive testing campaign would help to better calibrate the proposed model. The actual version of program is now able to take in account the shear behaviour in RC elements, which will permit a future exhaustive analysis campaign that would help to understand the behaviour RC building under earthquake loads.

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