NUMERICAL MODEL TO SIMULATE THE NON-LINEAR SHEAR BEHAVIOUR OF RC ELEMENTS

Humberto Varum [1], Hugo Rodrigues [2], Aníbal Costa [3]

Abstract: Seismic assessment of RC structures requires realistic and simple analytical models. In this paper is presented the model proposed and implemented in the program PORANL, to represent the RC buildings behaviour under severe earthquake loading. The response of RC elements to earthquake loads can be controlled by bending or shear behaviour, depending on the geometrical characteristics of the elements and on the reinforcement detailing. To represent the non-linear shear behaviour of RC elements, it was developed and implemented in the PORANL software a simplified model. In this paper is presented the proposed shear model and the results of its calibration based on tests on a full-scale building frame structure.

1. Introduction

From the observation of collapsed and severely damaged structures during recent earthquakes, it is clear the complex behaviour of reinforced concrete (RC) buildings, and particularly under seismic loadings. This fact underlines the need for numerical models that represent the behaviour of these structures at local and global levels. In the analysis of RC structures, subjected to seismic actions, the use of non-linear models allows to a more rigorous representation of its response [1]. In this paper is presented a simplified non-linear shear model for RC elements.

Typical gravity load's design of buildings results in design shear forces significantly lower than the shear forces that could be developed in a column for seismic demands. In some building structures its seismic response is controlled by the shear behaviour of its elements. For these structures, the shear behaviour and capacity of elements should be considered in the safety verification. The problem of shear strength and confinement is commonly more severe in corner columns, especially if the building has significant level of eccentricities. Earthquakes always confirm that a significant number of collapses occurs associated to short column mechanisms, due to its high stiffness, attracting much higher shear forces than the values for which they were designed. Short column mechanisms surges frequently associated to partial infilled walls due to openings [4].

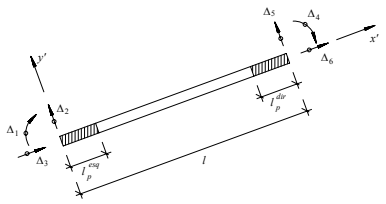


Fig. 1 Frame macro-element.

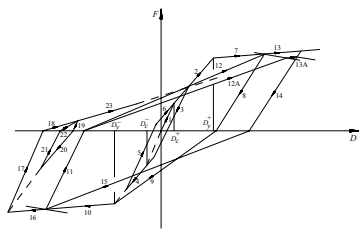


Fig. 2 Bending hysteretic model for RC elements.

The original version of the PORANL program was able to represent the non-linear bending behaviour of RC elements. In this software, 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 Fig. 1 [2].

[1] *Prof. Humberto Varum, Ph.D., University Aveiro in Portugal – Civil Engineering Department, hvarum@ua.pt*
[2] *Ing. Hugo Rodrigues, Ms.C, University of Aveiro in Portugal – Civil Engineering Department, hrodrigues@ua.pt*
[3] *Prof. Aníbal Costa, Ph.D., University Aveiro in Portugal – Civil Engineering Department, agc@ua.pt*

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 Fig. 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, internal cycles, etc.

2. Model for shear behaviour of RC elements

2.1. 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 stiffness of the structure, and therefore, controlling the deformation demands. Current analysis programs support non-linear models just in bending. A new non-linear shear behaviour model was proposed, and implemented in the PORANL computer program [2], and will be summarily described in the following.

2.2. Proposed macro-model

The non-linear shear behaviour model was implemented based on the frame macro-model available in the PORANL program 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 Fig. 1. The non-linear monotonic behaviour curve of an 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].

2.3. Hysteretic rules

In the shear model, the non-linear behaviour is characterized by hysteretic rules based on the Takeda's model [6], allowing to represent the response to cyclic loads depending on the material's behaviour (defined by the envelop curve and hysteretic parameters). The hysteretic rules are briefly exemplified in Fig. 3. The loading stiffness depends on the maximum force and displacement value 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:

$$K_r = \frac{F_{\max}}{d_{\max} - d_r} \tag{1}$$

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:

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

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 is given by Eq. 3:

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

The "Pinching" effect is important for elements were the shear behaviour is dominant. The pinching effect is represented dividing the reloading branch in sub-two branches with different stiffness (Fig. 4). The pinching effect is controlled through the parameter β, and depends on the maximum displacement reached previously. The strength degradation, for repeated cycles of certain distortion amplitude, was implemented considering interaction between the degradation in shear of one direction in the other.

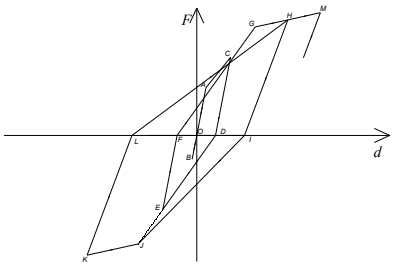


Fig. 3 Hysteretic rules for the proposed shear model.

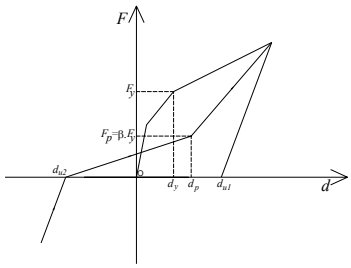


Fig. 4 "Pinching" effect.

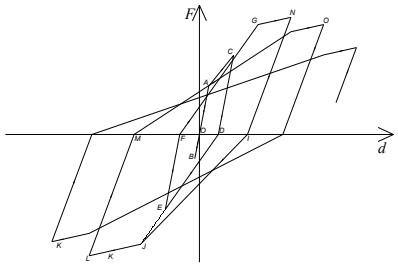


Fig. 5 Strength degradation.

3. Calibration of the shear model

The proposed macro-model to simulate the shear behaviour was verified using results obtained from an experimental campaign developed under the research network ICONS, addressing the seismic assessment and retrofitting of existing structures. Details on the test campaign and results can be found in [4]. The structure studied is a full-scale plane frame model with four storeys and three bays. The cross-sections' geometrical characteristics and the reinforcement detailing of the columns and beams, as well as the material properties can be found in [4].

To illustrate the ability of the proposed shear model, it were simulated the response of a column located at the first storey of the frame tested. The studied column was exhaustively instrumented (see Fig. 6 and 7-a). For the tests, it were installed in this column a set of 27 relative displacement transducers, distributed as represented in Fig. 6 and Fig. 7-a, witch allowed 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 global model for the column (Fig. 7-b). The column was simulated with the following boundary conditions (Fig. 7-b): a) displacements and rotations blocked at the base; b) compression axial force was applied, corresponding to the vertical loading; c) imposed lateral displacement and rotation at the top of the column, according to the measured results (local instrumentation) during the tests. For the imposed boundary conditions, two different analyses were performed. First, it was calculated the response of the column considering only its bending behaviour. Secondly, it was considered the bending and shear behaviour for the response estimation [5].

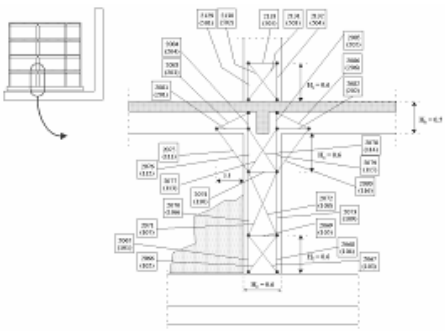
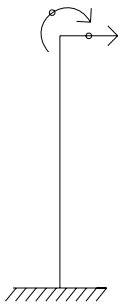


Fig. 6 Instrumentation set-up at the 1st storey strong-column.

a)



b)

Fig. 7 Studied column: a) Instrumentation; b) Global model adopted.

In Fig. 8 are represented the results in terms of column shear-drift (numerical and experimental results). For the second analysis, it were modelled the same imposed boundary conditions than the imposed for the first analysis, considering now the shear and bending behaviour of the column. In Fig. 9 are represented the column shear-drift evolutions.

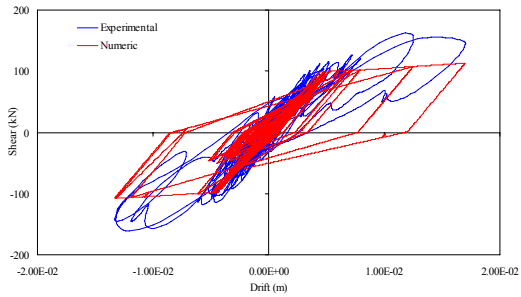


Fig. 8 Column shear-drift results considering only bending behaviour.

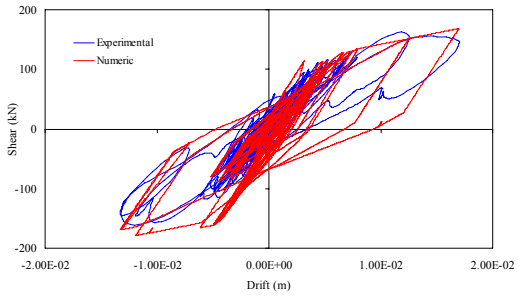


Fig. 9 Column shear-drift results considering bending and shear behaviour.

From the results obtained, it can be concluded that for RC elements with considerable shear stiffness, the bending non-linear models may not be able to accurately reproduce the global element behaviour under cyclic loading, particularly for high demand levels. The numerical results presented illustrates that the combination of the bending and shear behaviour provides a much better representation of the experimental results.

4. Final comments

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

References

[1] *Rodrigues, H; Romão, X.; Costa, A.; Varum, H. (2007)* - Integrated Graphical Environment for Support Nonlinear Dynamic Software for the Analysis of Plane Frames - IJSIMM, International Journal of Simulation Modelling, Vol. 6, N. 2, pp. 102-113, DAAAM International Vienna - ISSN 1726-4529 - June 2007.

[2] *Varum, H. (1996)* - Modelo Numérico para a Análise de Pórticos Planos de Betão Armado - MSc Thesis, Civil Engineering Department, University of Porto (in Portuguese).

[3] *Costa, A.G. (1989)* - Análise Sísmica de Estruturas Irregulares - PhD Thesis, Civil Engineering Department, University of Porto (in Portuguese).

[4] *Varum, H. (2003)* - Seismic Assessment, Strengthening and Repair of Existing Buildings - PhD Thesis, Department of Civil Engineering, University of Aveiro.

[5] *Rodrigues, H.; Varum, H.; Costa, A. (2008)* - A non-linear masonry infill macro-model to represent the global behaviour of buildings under cyclic loading - International Journal of Mechanics and Materials in Design, Vol. 4, N. 2, pp. 123-135 - ISSN 1569-1713 - June 2008.

[6] *Takeda, T.; Sozen, M.A.; Nielsen, N.N. (1970)* - Reinforced Concrete Response to Simulated Earthquakes - Journal Structural Division, ASCE, Vol. 36, No. ST12.