Out-of-plane behaviour of reinforced concrete members with single reinforcement layer subjected to cyclic axial loading: beam-column element simulation

A. Rosso, J. P. Almeida & K. Beyer

Earthquake Engineering and Structural Dynamics Laboratory (EESD)
École Polytechnique Fédérale de Lausanne (EPFL).

2016 NZSEE Conference

ABSTRACT: Earthquake loads can induce out-of-plane deformations in thin reinforced concrete (RC) walls that may lead to member out-of-plane failure or cause a premature in-plane collapse. Such instability phenomena have been observed after the recent earthquakes in Chile (2010) and New Zealand (2011). Walls with single layer of vertical reinforcement are more vulnerable to instability issues than the typical two-layer design. However, high material costs and the increasing demand of housing for low income population in Latin America (namely Colombia) over the last few years has prompted city administrations to build medium to high rise RC buildings using walls with single layers of vertical reinforcement.

The results of a recent experimental campaign on thin RC walls performed by the authors confirmed the relevance of this topic, underlining the need for further investigations to study the effect of different parameters on the out-of-plane response, such as loading history, wall thickness, and longitudinal reinforcement ratio. This effort is currently being carried out by idealizing the wall boundary region—which primarily triggers the instability mechanism—as an equivalent column axially loaded in cyclic tension and compression, as commonly hypothesized by the existing phenomenological models. This paper presents the first results of a numerical study consisting of the application of a beam-column model.

1 INTRODUCTION

Over the last few years Latin American city administrations have been urged to provide large amount of housing for low income population. As the land cost has increased significantly, one of the most common solutions has been the construction of medium to high rise reinforced concrete (RC) wall buildings. Due to the high material costs, most of these new residential buildings are constructed with very thin walls and a light amount of reinforcing steel placed in a single layer. After the recent earthquakes in Chile (2010) and New Zealand (2011), which caused significant damage and even the collapse of some RC wall buildings, it was found that in several cases the walls tended to buckle out-of-plane (Wallace et al. 2012; Sritharan et al. 2014). It should be noted that in Colombia the wall thicknesses are as low as 8 cm while in Chile and New Zealand the minimum wall thickness is nearly twice as large (15 cm). It is therefore to be feared that these South American buildings can perform poorly during a future earthquake if no retrofit interventions are carried out beforehand in the critical walls.

The first authors who studied the instability of RC walls were Goodsir and Paulay in 1985 (Goodsir 1985; Paulay and Goodsir 1985). The development of the mechanism can be summarized as follows (Goodsir 1985; Paulay and Goodsir 1985): at large in-plane curvature demands the boundary element develops large tensile strains that cause wide near-horizontal cracks across the wall thickness and yielding of the longitudinal reinforcement in tension. Upon unloading, an elastic strain recovery takes place but due to the plastic tensile strains accumulated in the rebars the cracks remain open. When reloading in compression and before crack closure, the compression force is resisted solely by the vertical reinforcement. This stage is typically accompanied by an incipient out-of-plane displacement, which occurs due to construction misalignments in the position of the two layers of reinforcement, eccentricity of the single layer of reinforcement, or eccentricity of the resultant vertical force. As long as the rebars retain a significant axial stiffness, the out-of-plane displacements tend to remain small. However, as compression increases, the rebars lose their stiffness due to the Bauschinger effect or plastification in compression and the lateral displacement of the entire boundary element will increases. Depending on the magnitude of the tensile strain previously attained (i.e., before unloading), the cracks may close (re-establishing compressive force transfer through concrete and contributing to straighten up the wall) or they may remain open (causing an abrupt increase of the out-of-plane displacements due to the reinforcement behaviour) possibly leading to wall buckling failure. Intermediate conditions, wherein cracks close at least partially, are also conceivable. Independently of the scenario that effectively takes place, the occurrence of out-of-plane displacements and second-order moments will affect the in-plane wall response and should therefore be taken into account.

The existing models developed to describe the out-of-plane buckling of RC walls (Paulay and Priestley 1993; Chai and Elayer 1999) assimilate the boundary element—which represents the part of the wall mainly involved in the instability mechanism—to an equivalent column axially loaded in tension and compression. The parameter that governs the occurrence of out-of-plane deformations has been identified as the magnitude of the maximum applied tensile strain prior to subsequent loading in compression. Past experimental campaigns on RC columns loaded in tension and compression (Goodsir 1985; Chai and Elayer 1999; Acevedo et al. 2010; Creagh et al. 2010; Chrysanidis and Tegos 2012; Shea et al. 2013) have confirmed this assumption, but these tests did not investigate the influence of other variables, such as the thickness of the specimens, the eccentricity of reinforcement—if only one layer is used—or the reinforcement ratio.

In order to study the influence of these variables on the out-of-plane response, efficient modelling techniques are required. The corresponding numerical simulation is challenging because of the need to account for a complex interaction between nonlinear geometric and material effects. The present study illustrates the application of a beam-column model to simulate the out-of-plane response of equivalent columns—representative of the boundary elements of a wall, as mentioned above—subjected to cyclic tensile and compressive loading.

2 DESCRIPTION OF THE NUMERICAL MODEL

As briefly discussed in the Introduction, wall sections with a single layer of reinforcement represent a critical case when studying the out-of-plane behaviour (see Figure 1a-b). Along the same rationale of using an equivalent column to describe the wall web edge behaviour, and considering the actual boundary conditions that restrain the wall in a real case, one could think of the simplified beam-column model depicted in Figure 1c-d for simulation purposes. Therein, the top rotational spring simulates the torsional stiffness of the top RC wall and slab, while a fixed bottom end is assumed to be representative of the effective boundary condition at the base of the test specimen. Several considerations on the choice of such boundary conditions are discussed in more detail in Section 4.4.

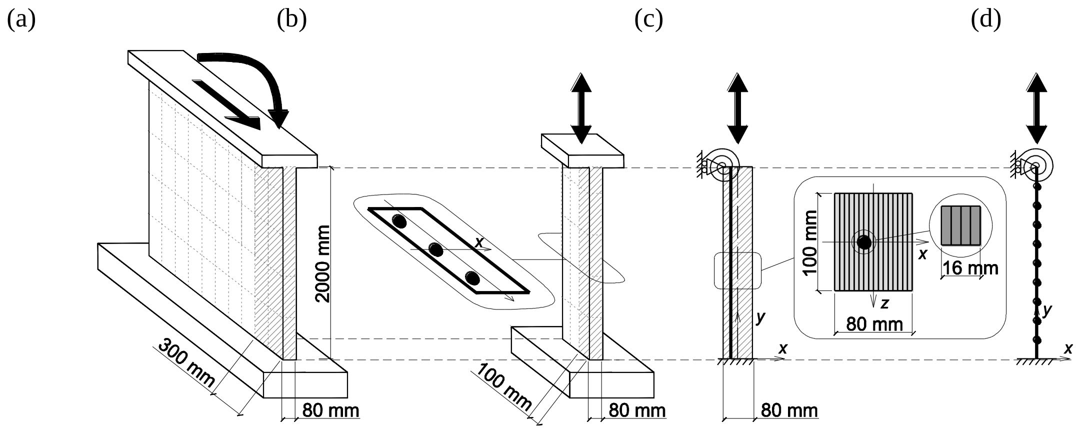

Figure 1 - (a) Wall subjected to seismic loading. (b) Idealization of the boundary element as a column loaded in tension-compression and identification of the single layer of reinforcement in the section. Description of the model: (c) boundary conditions and discretization of the section in fibres; (d) discretization in different force-based elements along the height.

This model was implemented by the authors to carry out finite element simulations that can be employed in engineering practice to assess the stability of wall boundary elements. The numerical simulations were performed with a 2D beam-column model using the software OpenSees (McKenna et al. 2000). To study the out-of-plane deformation of the equivalent column, subjected to axial tension-compression, only the outermost rebar at the extremity and the surrounding concrete section needs to be modelled (see Figure 1c). Numerical analyses of even such a simple member and loading are quite challenging because of several issues that may hinder convergence: (i) the sudden drop in concrete tensile strength; (ii) the fact that when the section is entirely cracked the only source of stiffness/strength is provided by a single rebar; (iii) the asymmetry of the section, which creates a variable out-of-plane moment along the height due to the geometric nonlinear effects and the imposed boundary conditions.

Two sources of nonlinearities are considered: (i) material: force-based elements are used (with five Gauss-Lobatto integration points) and the section is discretized into concrete and reinforcement fibres (see Figure 1c) to which nonlinear uniaxial stress-strain laws are associated; (ii) geometric: these effects are accounted for by using a corotational transformation—to consider the effect of large displacements—and by discretizing the column into several elements along the height, thus simulating the ‘small P-delta’ effect.

The reference model used in the following, equivalent to the boundary elements of two walls tested by Almeida et al. (2015), consists of a column 2000 mm tall, 80 mm thick and 100 mm long. A single rebar, modelled as a square of 16 mm, was placed at an eccentricity of 10 mm with respect to the centerline. The column (depicted in Figure 1d) was discretized in ten elements along the height and the section was discretised in 16 concrete and four steel fibres (see Figure 1c; Section 4.4 provides a more detailed discussion on this latter aspect). The concrete is modelled using an uniaxial Kent-Scott-Park law (Kent and Park 1971; Scott et al. 1982) with degraded linear unloading/reloading stiffness according to the work of Karsan-Jirsa (Karsan and Jirsa 1969) and no tensile strength (concrete compressive strength f'_c=30 MPa, concrete strain at maximum strength ε_{c0}=0.002), while the reinforcement is modelled considering an uniaxial Giuffrè-Menegotto-Pinto steel law (Giuffrè and Pinto 1970; Menegotto and Pinto 1973) with isotropic strain hardening (yield strength f_y=600 MPa, initial elastic tangent E_s=200 GPa, strain-hardening ratio b=0.005). The column is subjected to a single cycle of loading, imposing a displacement history, which first tensions the column (positive displacement) and then compresses it (negative displacement).

3 RESPONSE OF THE REFERENCE MODEL

The following results correspond to a case in which the column is subjected to a tensile displacement of +10 mm—which is large enough to yield the rebar in tension—and then to a compressive displacement of -2 mm.

Figure 2a depicts the vertical (axial) force-displacement response of the unit, showing that a plastic deformation has occurred. Figure 2b illustrates the imposed vertical displacement *vs* the out-of-plane displacement at the height where it was maximum (i.e. at midheight, see Figure 3a). It can be observed that, after attaining a large out-of-plane displacement, the latter is almost completely recovered. Moreover, it can be noted that the maximum out-of-plane displacement occurs just after attaining a compressive value of the vertical force, i.e. in the reloading phase, when the vertical displacement is small but still positive (red squares in Figure 2). This evidence was noted already in past experimental campaigns on RC walls (Goodsir 1985; Johnson 2010; Rosso et al. 2016). Figure 3 shows, for different values of imposed vertical displacement, the out-of-plane displacement profiles (Figure 3a), the bending moment diagrams (Figure 3b) and the curvature profiles (Figure 3c).

When the maximum positive imposed vertical displacement (+10 mm) is attained (blue triangles in Figure 2 and Figure 3), the global bending moment is negative and the out-of-plane displacement and the curvature are almost null. Upon reloading, the bending moment becomes positive and it can be observed that it is smaller in the sections experiencing large lateral displacements, i.e. around the column midheight, due to second order effects. When the vertical displacement reduces to +3.5 mm—identified by green circles in Figure 2 and Figure 3, corresponding to an out-of-plane displacement at midheight equal to -7.4 mm—the strain in the concrete fibres at midheight reaches a value of zero, indicating that the cracks start closing on the concave side of the deformed shape. Upon further reloading, the out-of-plane deformation and the bending moment keep increasing; it can be observed that the minimum (negative) value of the curvature is attained at midheight, while a maximum (positive) value is reached at the extremities, indicating that the cracks have started closing on the opposite side of the section. When the vertical displacement imposed reaches +3 mm—identified by red squares and lines in Figure 2 and in Figure 3—the out-of-plane displacement is at its maximum (-10.9 mm), and the crack closure extends along ~25 cm from the base and from the top, and ~100 cm at midheight. As progressively smaller displacements are imposed, the closure of further cracks causes an increase of the out-of-plane stiffness of the column, triggering a straightening of the column with consequent reduction of the curvature (cyan stars in Figure 2 and in Figure 3). Finally, when the imposed vertical displacement becomes negative (compressive displacement), the out-of-plane deformation is completely recovered, the bending moment profile is again linear and the curvature profile is almost null (magenta triangles in Figure 2 and in Figure 3).

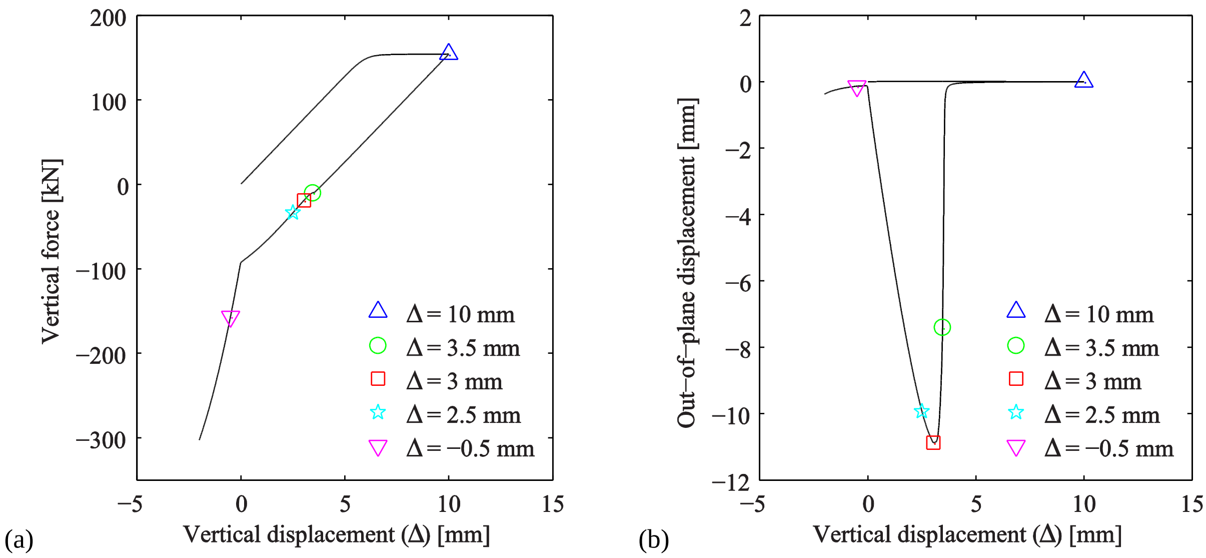

Figure 2 - (a) Vertical force-displacement response of the reference model; (b) Imposed vertical displacement *vs* out-of-plane response at the height where it was maximum, i.e. at midheight.

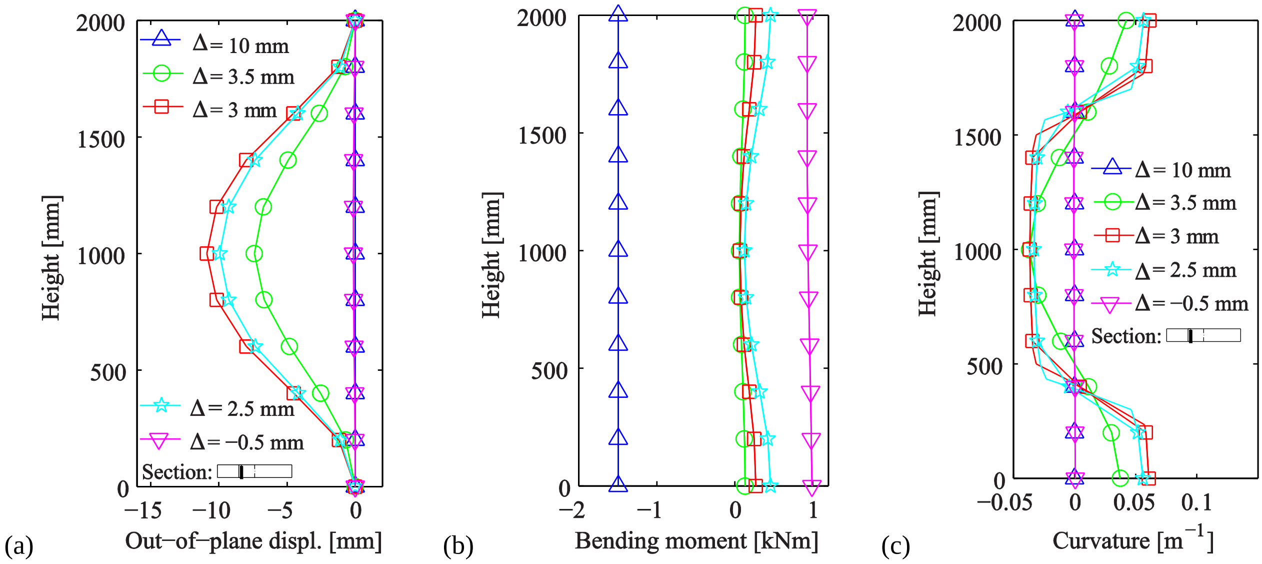

Figure 3 - Profiles along the height at imposed vertical displacements: (a) out-of-plane displacements; (b) bending moments; (c) curvatures.

It is interesting to observe that the out-of-plane deformation of the column occurs towards the same side on which the rebar is eccentrically placed with respect to the centreline of the section. In fact, when the imposed displacement reverses (i.e. when unloading from tension), the rebar represents the only source of out-of-plane stiffness in the section since the cracks are still open and therefore the concrete fibres do not contribute. Therefore, considering the case of a simply supported beam, the cracks are necessarily forced to close first in the opposite side of the section in which the rebar is placed. This behaviour, reproduced in the numerical simulations, has been also observed in the experimental campaign on thin walls with a single layer of reinforcement performed by the authors (Rosso et al. 2016).

4 INFLUENCE OF DIFFERENT VARIABLES ON THE RESPONSE

The reference model described above was used to study the sensitivity of the out-of-plane response to different parameters, which is addressed in the three following sub-sections. Section 4.4 discusses several critical points of the simulation, such as the definition of the boundary conditions and the modelling of the rebar.

4.1 Maximum applied tensile strain

As already mentioned in the Introduction, several past experimental and analytical studies identified the magnitude of the maximum applied tensile strain prior to subsequent loading in compression as the key parameter that triggers instability (Goodsir 1985; Paulay and Priestley 1993; Chai and Elayer 1999; Acevedo et al. 2010; Creagh et al. 2010; Chrysanidis and Tegos 2012; Shea et al. 2013). With the aim of checking this observation with the finite-element model, three different vertical displacement histories were imposed: up to a positive tensile displacement (Δ_{max}) of +4 mm, +8 mm or +12 mm, and then to a negative compressive displacement of -2 mm.

Figure 4a shows the vertical force-displacement response of the specimen and Figure 4b illustrates the imposed vertical displacement *vs* out-of-plane displacement at midheight (where it was larger). It can be noted that when the column is loaded up to +4 mm the reinforcement in tension, it does not reach the yield strain; when unloading, the reinforcement thus remains elastic—hence keeping a significant stiffness—and the out-of-plane displacement is null (green line in Figure 4b). In fact, the occurrence of significant plastic deformations is an important indicator of out-of-plane instability, since as soon as the rebar starts losing its stiffness due to the Bauschinger effect, an out-of-plane deformation develops. From Figure 4b it can be observed that larger applied positive vertical displacements results in larger maximum out-of-plane displacements. Moreover, it can be noted that the out-of-plane displacement is not directly proportional to the maximum tensile strain, as an increase of 50% on the imposed displacement (+12 mm *vs* +8 mm) yields an out-of-plane deformation four times larger. Finally, it can be observed that lateral deformations start occurring at a vertical displacement (just after the beginning of the reloading phase), which is approximatively proportional to the maximum displacement imposed.

4.2 Thickness

According to the main international codes, the construction of thin walls with a single layer of longitudinal reinforcement is allowed (Rosso et al. 2016). In general, the codes impose limits on the height to thickness ratio of walls, and in several cases the minimum thickness required is 100 mm. However, if second order analyses are carried out, the thickness can be reduced to smaller values, hence in several South American countries (namely Colombia) it is common practice to build very thin walls, 80-100 mm thick, with a single layer of reinforcement.

In order to test the influence of this parameter, the reference model was subjected to the same reference displacement history described in Section 3 (+10 mm in tension, -2 mm in compression) using three different thicknesses (b_w): 80 mm, 100 mm and 120 mm. The results show that the out-of-plane displacements—which occur almost at the same value of imposed vertical displacement—attain smaller values when the thickness is larger (see Figure 5a), therefore reducing the possible contribution of this deformation mode to the member failure.

4.3 Longitudinal reinforcement ratio

In general, current design practice of RC walls favours section layouts with larger reinforcement ratios in the boundary elements than in the web. This design rule is not always followed, and sometimes the reinforcement used in the web is kept also in the boundary elements. The use of different boundary/web layouts is particularly common in the case of walls with a single layer of reinforcement in which the rebars used in the web have a small diameter, in general of 5-8 mm.

Therefore, to assess the influence of this variable, the reference model—subjected to the same imposed vertical displacement described in Section 3—was used to test the influence of the reinforcement diameter (d_{bar}) on the response, modelling the rebar as a square (see Section 2) of 8 mm, 16 mm and 24 mm. Figure 5b shows that a larger diameter provides a greater stiffness to the section and hence the column experiences smaller out-of-plane deformations. Although this finding seems quite intuitive, further research is required to reconcile it with the findings from existing phenomenological models (Paulay and Priestley 1993; Chai and Elayer 1999), which indicate that the increase of the reinforcement ratio in the boundary element reduces the maximum tensile strain corresponding to the onset of wall buckling (Rosso et al. 2014).

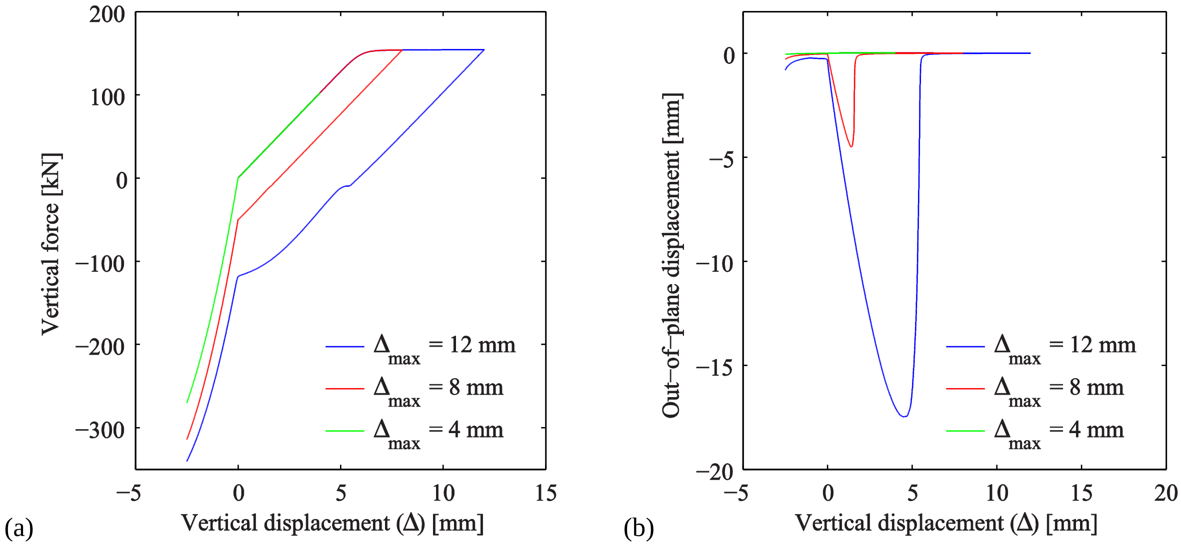

Figure 4 - (a) Vertical force-displacement response of the reference model subjected to different displacement histories; (b) Corresponding imposed vertical displacement *vs* out-of-plane displacement at the height where it was maximum, i.e. at midheight.

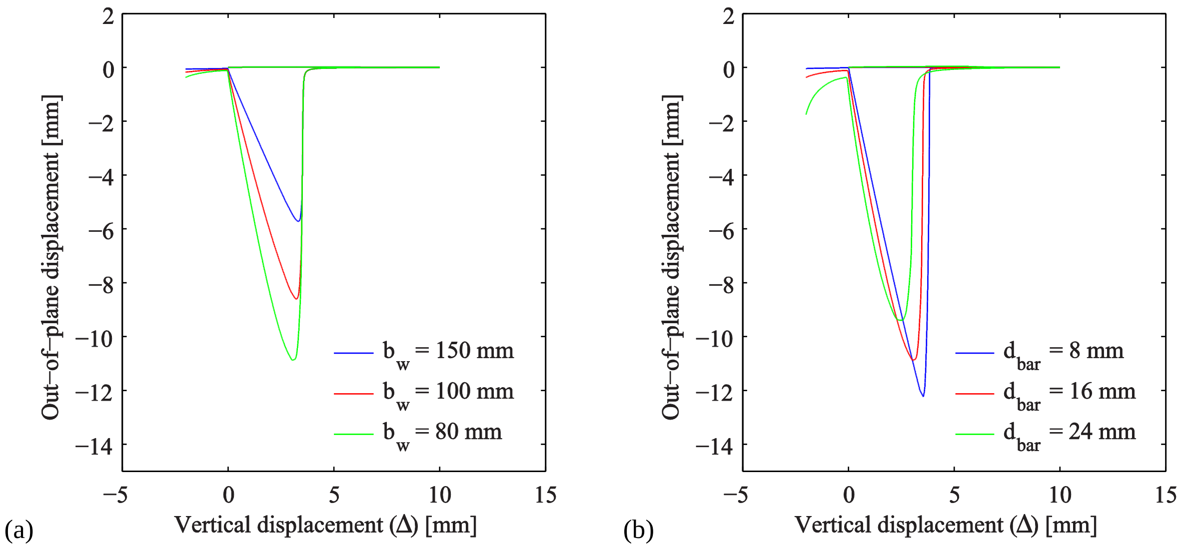

Figure 5 - Imposed vertical displacement *vs* out-of-plane displacement at the height where it was maximum, i.e., at midheight: (a) for different thickness values; (b) for different reinforcement ratios.

4.4 **Boundary conditions and numerical simulation issues**

The existing phenomenological models mentioned in the Introduction (Paulay and Priestley 1993; Chai and Elayer 1999) assume the boundary conditions of the equivalent column, representative of the end region of the wall, as pin-pin. Assigning these boundary conditions to a column where fibres are used to model an eccentric rebar brings, however, several problems. In fact, since no reaction moments can be developed at the extremities, when a tensile positive displacement is imposed the equilibrium of the internal moment (which has to be null) at the extremity sections must be achieved through the development of compressive stresses in the extreme concrete fibres on the same side of the section where the bar is placed. Very significant positive curvatures at the extremities have thus to be developed, causing a very large out-of-plane deformation of the column. This behaviour is not representative of the reality. Hence, the assumption of a rotational spring at the top and of a fixed restraint at the base allows for, on the one hand, to realistically equilibrate the internal moments at the extremities and, on the other, to have a better description of the real boundary conditions, simulating the torsional stiffness of the RC wall and slab.

Concerning the range of values that can be assumed for the stiffness of the rotational spring, the latter has been defined between $K_{sp}=10^8$-10^{20} N·mm. Within this range, the results obtained for the out-of-plane displacements were rather insensitive to the assumed spring stiffness. For smaller values of the rotational stiffness, the internal equilibrium problems described above arise, while for larger values it was seen that numerical convergence problems often occur.

Another critical issue of the numerical simulation, partially related to the definition of the boundary conditions, has to do with the discretization of the bar into several fibres. When the column is subjected to axial loading, the axial force is approximately constant while the bending moment varies along the height (particularly when second order effects become relevant). In the specific phase where the column is subjected to tensile loads, such variable internal forces along the height are equilibrated solely by the rebar (since the cracks are open and the concrete does not contribute), which implies that the latter is required to develop a resisting bending moment. For this reason, hence, it is necessary to discretize the rebar into several fibres (e.g. four fibres as described for the reference model in Section 2) and not only in one, which is the usual procedure when modelling reinforced concrete sections through fibre discretisation.

5 **CONCLUSIONS AND FUTURE WORK**

This paper presents the use of beam-column elements to simulate the behaviour of RC columns subjected to axial cyclic loads. These columns represent the boundary element of thin RC walls with a single layer of reinforcement when subjected to horizontal loading, e.g. the seismic action. This typology of walls is representative of current design practice in several countries in South America, namely Colombia. The aim of the numerical simulation is to study the out-of-plane response of these walls when subjected to cyclic loading. In fact, when the equivalent column is compressed after undergoing a significant tensile load, lateral deformation (i.e. out-of-plane) can occur, triggering a failure due to global instability, which is not considered in common RC wall design.

After a general description of the finite element model, which uses an element force-based formulation with discretization of the section in fibres, its response under tension-compression loading was discussed in detail, with respect to the evolution of the bending moment, curvature and out-of-plane displacement profiles. It was shown that the model is able to capture some of the most important behavioural features of the out-of-plane instability.

A reference model was tested under an imposed cyclic vertical displacement (tension followed by compression) in order to study the sensitivity of the response with respect to several parameters:
(i) Loading protocol: different values of maximum tensile positive displacement have been imposed, showing that the corresponding plastic deformation controls the maximum value of out-of-plane displacement attained upon reloading in compression. In fact, only when the reinforcement stiffness reduces considerably (because of the Bauschinger effect and subsequent plastification in compression) and the cracks are still open, large out-of-plane deformation can take place.
(ii) Column thickness: several international codes allow building wall sections with a single layer of

reinforcement and thickness as low as 80-100 mm; the results of the numerical simulation have shown that, as expected, a thinner section is more susceptible to develop larger out-of-plane deformations.
(iii) Reinforcement ratio: the employed model shows that the out-of-plane deformation reduces when bars with a larger diameter are used. This finding, which seems quite intuitive, is somewhat in contradiction with the existing phenomenological models and therefore more investigation is required.

Finally, several issues related to the assigned boundary conditions and other critical points of the numerical simulation were discussed. The present work represents an early stage of a broader study involving numerical modelling and experimental testing of RC members subjected to tensile and compressive loading. The preliminary results showed that the numerical model seems to be a promising simple tool for assessing thin RC walls with a single layer of reinforcement subjected to seismic loading, with respect to their vulnerability against out-of-plane instability.

REFERENCES

Acevedo CE, Creagh A, Moehle JP, et al (2010) Seismic vulnerability of non-special boundary element of shear wall under axial force reversals. Florida International University and University of California, Berkley, U.S.

Almeida JP, Prodan O, Rosso A, Beyer K (2015) Tests on thin reinforced concrete walls subjected to in-plane and out-of-plane cyclic loading (manuscript submitted). Earthq. Spectra

Chai YH, Elayer DT (1999) Lateral stability of reinforced concrete columns under axial reversed cyclic tension and compression. ACI Struct J 96:1–10.

Chrysanidis TA, Tegos IA (2012) The influence of tension strain of wall ends to their resistance against lateral instability for low-reinforced concrete walls. 15th World Conf. Earthq. Eng.

Creagh A, Acevedo C, Moehle JP, et al (2010) Seismic performance of concrete special boundary element. University of Texas at Austin and University of California Berkley, U.S.

Giuffrè A, Pinto PE (1970) Il comportamento del cemento armato per sollecitazioni cicliche di forte intensità. G. del Genio Civ. 5:

Goodsir WJ (1985) The design of coupled frame-wall structures for seismic actions. University of Canterbury, Christchurch, New Zealand

Johnson B (2010) Anchorage detailing effects on lateral deformation components of RC shear walls. University of Minnesota, Minneapolis, U.S.

Karsan ID, Jirsa JO (1969) Behavior of Concrete Columns with Double-Head Studs Under Earthquake Loading: Parametric Study. ASCE J Struct Div 95:2543–2563.

Kent DC, Park R (1971) Flexural members with confined concrete. J Struct Div ASCE 97:1969–1990.

McKenna F, Fenves GL, Scott MH, Jeremic B (2000) Open System for Earthquake Engineering Simulation (OpenSees). Pacific Earthquake Engineering Research Center, University of California, Berkeley, U.S.

Menegotto M, Pinto PE (1973) Method of analysis for cyclically loaded reinforced concrete plane frames including changes in geometry and nonelastic behaviour of elements under combined normal force and bending. IABSE Symp. Resist. Ultim. Deform. Struct. Acted by Well Defin. Repeated Loads

Paulay T, Goodsir WJ (1985) The ductility of structural walls. Bull New Zeal Natl Soc Earthq Eng 18:250–269.

Paulay T, Priestley MJN (1993) Stability of ductile structural walls. ACI Struct J 90:385–392.

Rosso A, Almeida JP, Beyer K (2016) Stability of thin reinforced concrete walls under cyclic loads: state-of-the-art and new experimental findings. Bull Earthq Eng 14:455–484.

Rosso A, Almeida JP, Constantin R, et al (2014) Influence of longitudinal reinforcement layouts on RC walls performance. Second Eur. Conf. Earthq. Eng. Seismol.

Scott BD, Park R, Priestley MJN (1982) Stress-Strain Behavior of Concrete Confined by Overlapping Hoops at Low and High Strain Rates. ACI J 79:13–27.

Shea M, Wallace JW, Segura C (2013) Seismic performance of thin reinforced concrete shear wall boundaries. University of California Los Angeles, U.S.

Sritharan S, Beyer K, Henry RS, et al (2014) Understanding poor seismic performance of concrete walls and design implications. Earthq Spectra 30:307–334.

Wallace JW, Massone LM, Bonelli P, et al (2012) Damage and Implications for Seismic Design of RC Structural Wall Buildings. Earthq Spectra 28:S281–S299.