16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 2539

Registration Code: S-B1463497555

EXPERIMENTAL TESTS ON THE OUT-OF-PLANE RESPONSE OF RC COLUMNS SUBJECTED TO CYCLIC TENSILE-COMPRESSIVE LOADING

A. Rosso[1], J.P. Almeida[2], L. Jimenez[3], A.P. Guerrero[4], C.A. Blandon[5], R. Bonett-Díaz[6], K. Beyer[7]

[1] *PhD candidate, Earthquake Engineering and Structural Dynamics Laboratory (EESD), École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, angelica.rosso@epfl.ch*

[2] *Post-doctoral Researcher, Earthquake Engineering and Structural Dynamics Laboratory (EESD), École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, joao.almeida@epfl.ch*

[3] *MSc student, School of Civil Engineering, Universidad del Valle, Cali, Colombia, lisandro.jimenez@epfl.ch*

[4] *Professor, School of Civil Engineering, Universidad del Valle, Cali, Colombia, patricia.guerrero@correounivalle.edu.co*

[5] *Associated Professor, EIA University, Medellín, Colombia carlos.blandon@eia.edu.co*

[6] *Professor, University of Medellin, Medellín, Colombia, rbonett@udem.edu.co*

[7] *Assistant Professor, Earthquake Engineering and Structural Dynamics Laboratory (EESD), École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, katrin.beyer@epfl.ch*

Abstract

Over the last few years the increasing demand of housing for low income population in Colombia and several neighboring countries, associated to the significant increase of cost of land, has prompted construction companies to build medium to high rise reinforced concrete (RC) wall buildings. Most of these new residential buildings are constructed with walls that have thicknesses as low as 80 mm and are only lightly reinforced. The recent earthquakes in Chile (2010) and New Zealand (2011) have caused significant damage to some of the RC walls, some of which tended to buckle out-of-plane. In Colombia the wall thicknesses are significantly thinner than in Chile or New Zealand and is therefore is to be feared that these buildings may present the same out-of-plane failure mode during a future earthquake. Furthermore, many of the walls have only a single vertical reinforcement layer, which could increase the out-of-plane instability, as it will be shown in this paper.

Although recent experimental tests have shown that wall out-of-plane deformations can extend throughout a relatively large part of the wall length, the boundary regions are the critical zones that control the development of associated failure modes. For thin walls behaving predominantly in flexure those boundary regions are subjected to mainly axial strains, and hence testing equivalent RC columns under cyclic axial tension and compression provides direct insights into the influence of the parameters triggering wall instability and possible out-of-plane failure.

Within a collaborative project between the École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland and the Universidad del Valle, the EIA University, and the University of Medellin in Colombia, equivalent RC columns with a single vertical reinforcement layer are tested at EPFL in order to investigate the effect of loading history, reinforcement ratio and eccentricity of the longitudinal rebars with regard to the element axis ration the out-of-plane response.

The paper presents the details of this recent experimental campaign, describing the geometry and the reinforcement layout of the specimens, the test setup, the extensive instrumentation used, and the results obtained from the first tests. The experimental findings allowed to draw initial conclusions on the development of the out-of-plane instability, on the particularities of single layer reinforcement members and on the development of out-of-plane failures.

Keywords: lateral instability of RC walls; out-of-plane behavior of RC members; thin RC walls; experimental tests.

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 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 [1,2]. 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 critical walls from these South American buildings may develop out-of-plane failures during a future earthquake if no retrofit interventions are carried out beforehand.

The first authors who studied the instability of RC walls were Goodsir and Paulay in 1985 [3,4]. The development of the out-of-plane mechanism can be summarized as follows [5,6]: 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 compression increases, the longitudinal reinforcement may yield, leading to an abrupt reduction in out-of-plane stiffness and a consequent increase in the corresponding displacements. 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.

Very few experimental campaigns addressed specifically the behaviour of thin walls prone to out-of-plane buckling. The quasi-static cyclic tests for which significant global out-of-plane deformations along the wall height were observed [3,7–10] showed that out-of-plane instability affects in general thin walls, both with one or two layers of longitudinal reinforcement. The failure modes that these walls may develop are rather complex, as they often involve global wall instability, local bar buckling and concrete crushing. Two thin RC walls with one layer of reinforcement were tested at EPFL applying a uni- and bi-directional horizontal loading respectively. The entire experimental data set is available to the public [10]. Fig. 1a shows the employed test setup when applying uni-directional loading. One test unit developed significant out-of-plane deformation (see Fig. 1b), attaining a maximum lateral displacement larger than half the section thickness, which was almost completely recovered before the wall finally failed due to crushing of the concrete. These tests confirmed how thin walls are prone to develop out-of-plane instability and may cause an unexpected premature failure [11].

Existing models that describe the out-of-plane buckling of RC walls [5,6] approximate the boundary element—which represents the part of the wall mainly involved in the instability mechanism—by an equivalent column, which is 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 [5]. Past experimental campaigns on RC columns loaded in tension and compression [3,6,12–15] have confirmed this assumption, but these tests did not investigate the influence of other variables, such as the thickness of the specimens, the presence of a single layer of reinforcement and its eccentricity with respect to the centerline of the section or the reinforcement ratio.

Within a collaborative project between the École Polytechnique Fédérale de Lausanne (EPFL), the University of Valle, EIA Unversity and the University of Medellin, in Colombia, an experimental campaign on 12 equivalent RC thin columns (the specimens are named 'TC') with a single layer of vertical reinforcement is carried out at EPFL. In the following, the preliminary results obtained from the experimental campaign will be presented.

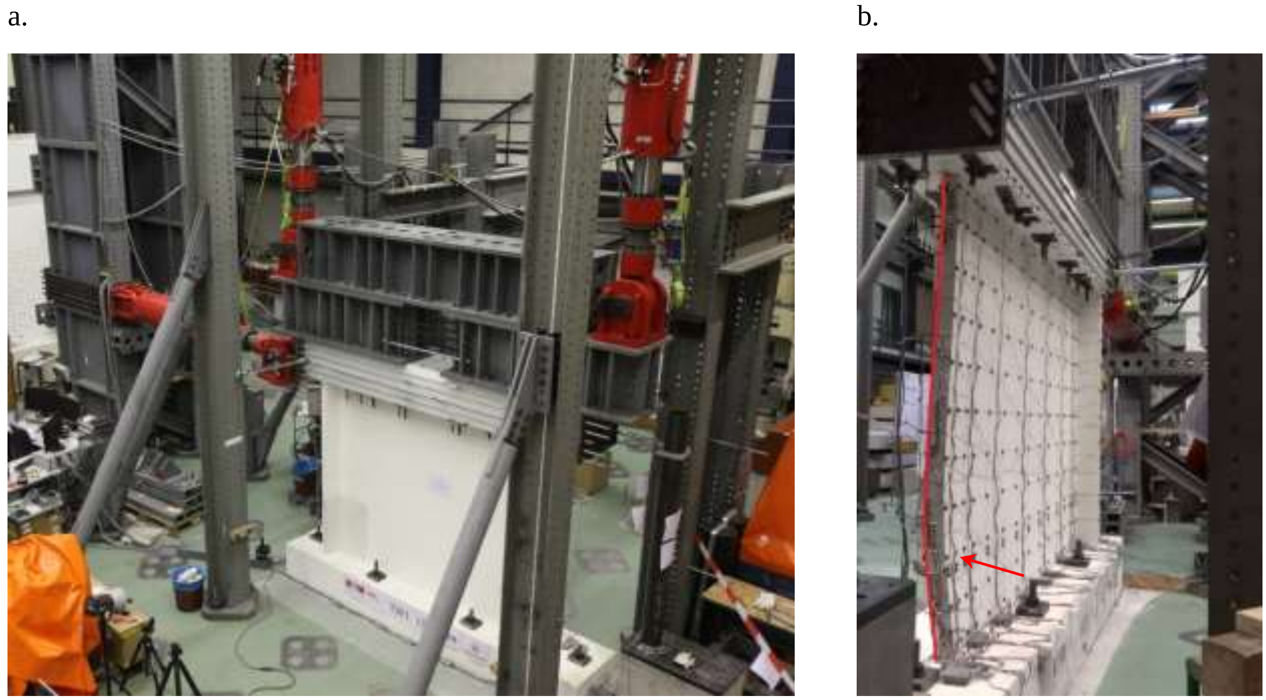

Fig. 1 – a. Test setup used for testing thin walls in a past experimental campaign. b. Wall test unit at maximum out-of-plane displacement.

2. Description of the specimens and of the test setup

The experimental campaign is still in progress and only three columns have been tested so far (TC10, TC11 and TC12). The specimens are representative of a full-scale boundary element of a thin wall.

2.1 Geometrical and mechanical characterization

The aim of the initial tests was to verify the reproducibility of the experiments and to study the sensitivity to the loading protocol. The first three columns tested were geometrically identical. The cross-section was 300 mm long and 100 mm thick (see Fig. 2a), and the reinforcement—placed in a single layer at an eccentricity of 8 mm with respect to the centerline of the section, see Fig. 5b—consisted of three bars of diameter 16 mm (reinforcement ratio ρ_c=2.01%). The horizontal reinforcement consisted of 16 bars of diameter 6 mm placed at a distance of 150 mm (reinforcement ratio ρ_h=0.19%). The columns were 2.4 m high, and the foundation and the head were RC blocks designed as stiff rigid members (see Fig. 2b).

The concrete strengths were f'_c=33.6 MPa (elastic modulus E_c=29667 MPa) and f'_c=32.9 MPa (elastic modulus E_c=28900 MPa) for specimens TC10-11 and TC12 respectively, while the characteristics of the reinforcement were f_y=515 MPa and f_u=620 MPa, at yielding and rupture respectively.

2.2 Test setup and loading protocol

The test setup used in the experimental campaign is shown in Fig. 2c-d. The two rigid RC blocks on top and at the base were clamped—using 12 prestressed bars per block—between four steel profiles, which were connected to the plates of a press. The top of the testing machine was fixed, while the piston at the base has a stroke of ±125 mm, and a force capacity of +2.5 MN in tension and -10 MN in compression.

The test was performed in deformation control. The vertical displacements imposed were evaluated averaging the measurements provided by four vertical LVDTs measuring the elongation along the four edges of the column (three LVDTs can be seen in the bottom part of Fig. 2c). The three-dimensional displacement fields of the two shorter sides (North and South faces, see Fig. 2a-b) were recorded using an optical triangulation measurement system—the employed hardware and software was the commercial system NDI Optotrak Certus HD [16], and the two cameras used can be seen in Fig. 2d—through a grid of more than 180 infrared light emitting diodes (LEDs) glued to the surfaces. The LEDs were placed on a regular grid of 40 mm in the horizontal direction and 100 mm in the vertical one (see Fig. 2c).

The loading protocol consisted of cyclic axial displacements. The peak displacements in negative direction (compression) were always the same (–0.8 mm). This value corresponds to an average compressive stress of $0.3 \cdot f'_c$, such that the concrete behaved almost elastically in compression before out-of-plane displacements developed. The peak displacements in positive direction (tension) were increased every other cycle. The following positive peak displacements were applied: 1.5 mm $\rightarrow$ 3 mm $\rightarrow$ 6 mm $\rightarrow$ 9 mm $\rightarrow$ 12 mm $\rightarrow$ 15 mm $\rightarrow$ 18 mm for TC10-11, and 3 mm $\rightarrow$ 6 mm $\rightarrow$ 12 mm $\rightarrow$ 24 mm for TC12. The peak values of the imposed displacements are named load stages (LS), and a full description of the displacement histories can be found in Fig. 3a.

3. Test observations

After concluding the test of the first three specimens, several verifications on the setup were performed—in order to control the test machine operation, the boundary conditions and the instrumentation used—and the results have shown that the overall behaviour of the setup was rather satisfactorily. In general, the responses of the specimens were consistent, and the data collected allowed to obtain new information on the development of the out-of-plane instability.

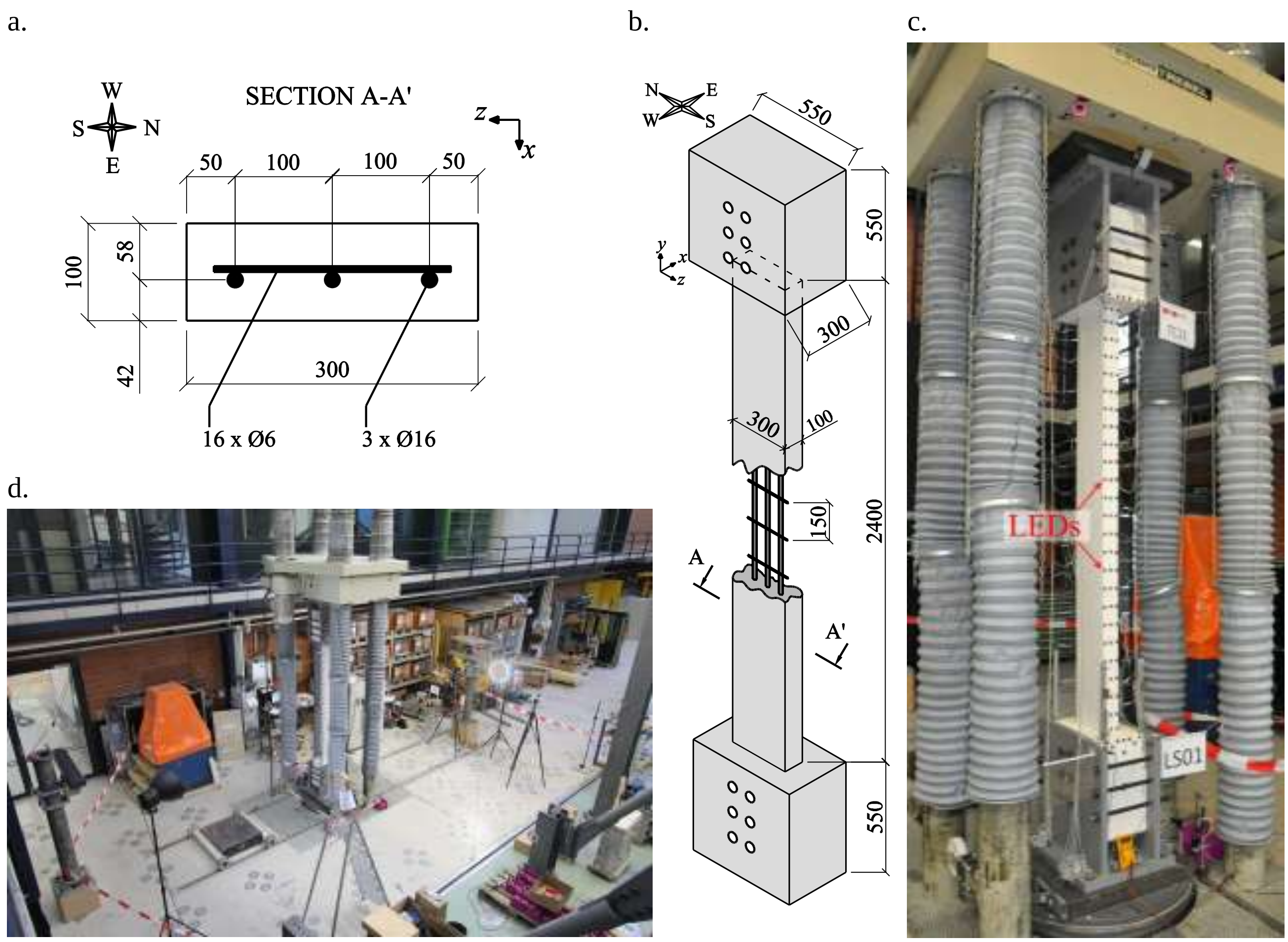

Fig. 2 – Geometrical characteristics of columns TC10-11-12: a. sectional view, b. 3D view (all dimensions in mm). c. and d. Views of the testing machine and instrumentations used.

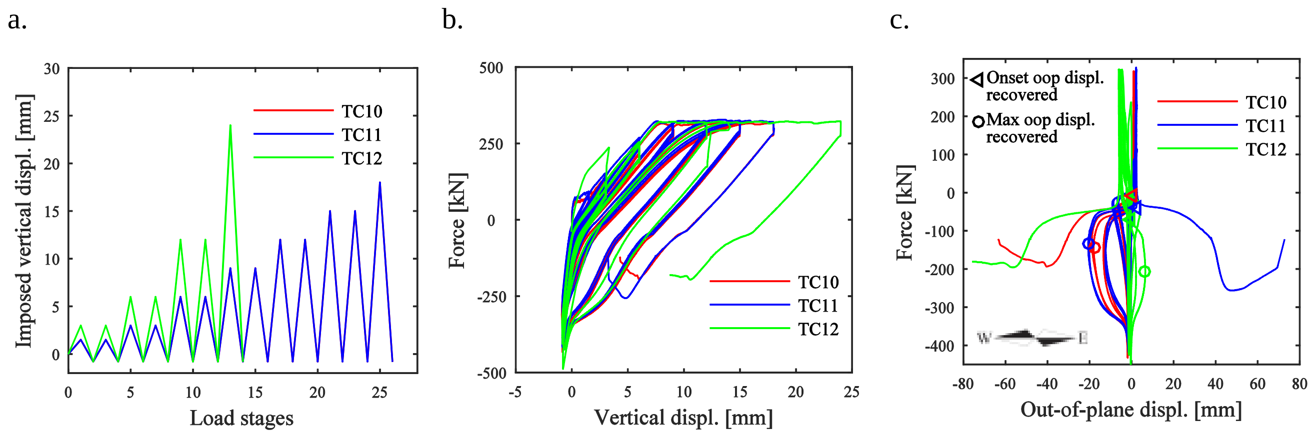

Fig. 3 – a. Imposed vertical displacement histories; b. Hysteretic curves of the three specimens; c. Maximum out-of-plane displacement at midheight *vs* vertical force.

Fig. 3b shows the axial force-displacement responses of the three specimens tested. The curves display a stable hysteretic behaviour with appreciable dissipation of energy and plastic deformation in tension. Just after having reached the maximum tensile displacement, a small drop in the force can be observed: this is related to the fact that the test after each load stage was stopped for a certain period in order to take pictures and collect information on the crack development; this break caused a small reduction in the pressure of the pump of the testing machine and relaxation of the stresses in the rebars and concrete. All the tests were stopped when the out-of-plane deformation attained was so large that concrete crushing in the plastic hinges took place and it was evident that the lateral displacement would not be recovered if the compressive loads were further increased. In the following, the attainment of this condition will be referred to as failure of the specimen.

Fig. 3c shows for the three tested specimens the vertical force *vs* the out-of-plane displacement attained at midheight of the columns. All three specimens attained significant lateral deformation during loading. The figure further shows that the onset of out-of-plane deformation (note that the triangles in the figure refer to the beginning of out-of-plane deformation during the last cycle in which the lateral displacement was still recovered) always occurred when the column had just started to undergo compression (negative force), as already observed in past experimental tests on thin walls [3,9,11]. Moreover, Fig. 3c and Fig. 4a show that the maximum out-of-plane displacements still recoverable (represented by circles in the figures) were attained in all three specimens at similar values in terms both of force that vertical displacement. Finally, in the cycle leading to failure, the out-of-plane displacement seemed for all three specimens first to stabilize before increasing again, which led then to the failure of the column due to crushing of the concrete in the plastic hinges.

All three specimens failed after having attained an average vertical tensile strain of 0.0075 (Fig. 4b), corresponding to an applied vertical displacement of 18 mm (note that in TC12 the cycle at 18 mm was skipped, and the column failed after a vertical displacement of 21 mm). The last cycle in which the out-of-plane deformation was recovered corresponded to an average tensile strain of 0.005 for TC12 and 0.00625 for TC10-11. This suggests that the critical maximum tensile strain after which failure is attained lies between 0.00625 and 0.0075. The following paragraphs discuss the response of each column.

3.1 TC10

For specimen TC10, after the first tensile displacement was applied (1.5 mm, equivalent to a tensile strain of 0.000625) several cracks developed along the height, roughly at a distance equal to the spacing between the horizontal reinforcement (150 mm). The first significant out-of-plane displacement was observed to occur when loading in compression after a tensile displacement of 12 mm (equivalent to a tensile strain of 0.005), as shown in Fig. 4a. Before failure, at a vertical displacement of 18 mm, the largest cracks were concentrated at the top of the column, at midheight (one large crack at around 1100 mm from the foundation) and above the base. When loading back into compression, the test was stopped after a large irrecoverable out-of-plane displacement at midheight of around to 70 mm was attained. At this point concrete crushing was already quite extensive in the plastic hinge at midheight, see Fig. 5d. On the other hand, almost no damage was observed at the extremities, see Fig. 5a.

From Fig. 3c and Fig. 4a it can be noted that the lateral deformation, as well as the failure, occurred towards West, therefore on the opposite side of the section where the longitudinal rebars were eccentrically placed (see Fig. 5a). The failure mechanism seems to consist in the development of three plastic hinges: one roughly at midheight, clearly visible in Fig. 5b, and two at the extremities. This can be observed also in Fig. 4c, which shows the deformed profile as computed through the optical measurements and the plastic hinges occurring at around 100, 1100 and 2200 mm above the base.

a. b. c.

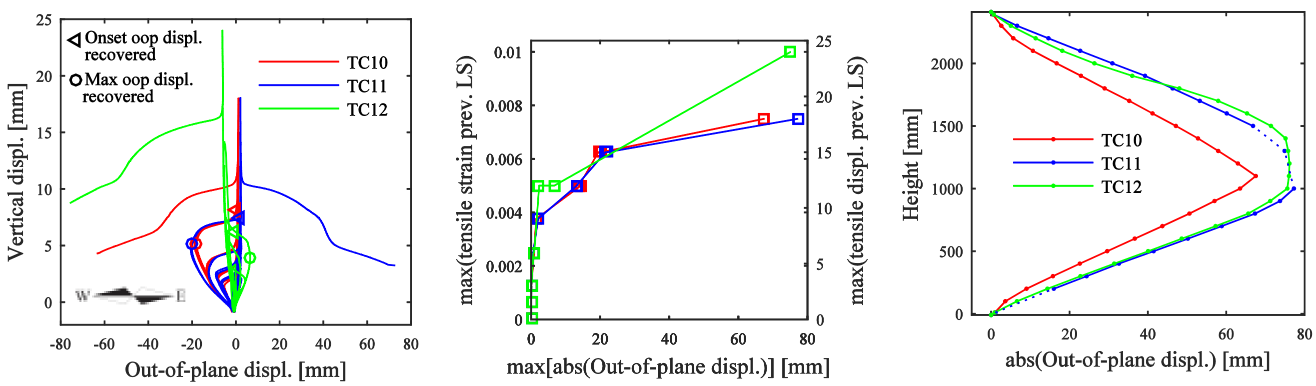

Fig. 4 – a. Imposed vertical displacement *vs* out-of-plane (oop) displacement at midheight; b. Maximum out-of-plane displacement attained between two consecutive LS *vs* axial tensile strain attained at previous LS; c. Out-of-plane displacement profile along the height when the tests were stopped.

a. b. c. d.

e.

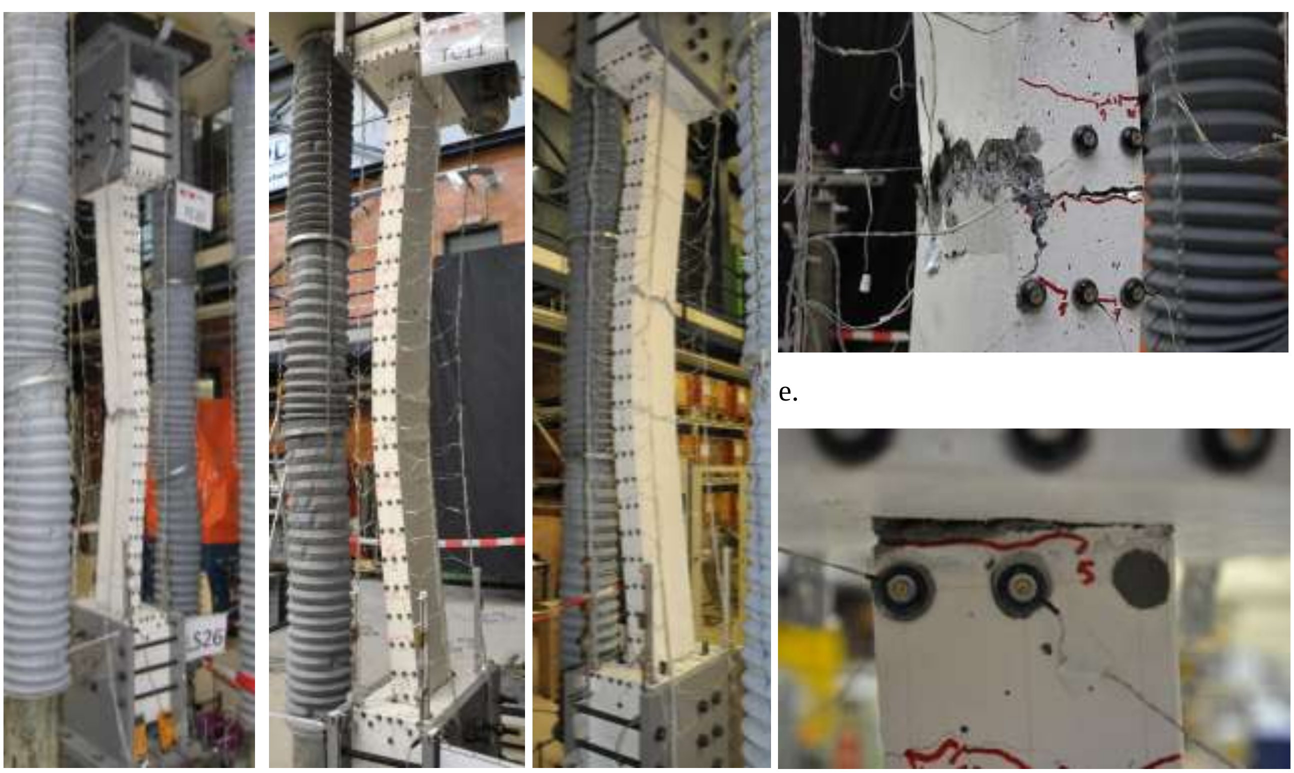

Fig. 5 – View of the specimens after failure: a. TC10 (N-E view), b. TC11 (N-W view), c. TC12 (S-E view). Details: d. crack at midheight in TC10 (N-E view); e. crack on top in TC11 (South view).

3.2 TC11

The responses of specimens TC11 and TC10 were very similar, with a consistent out-of-plane behaviour—lateral deformation towards West, see Fig. 4a—until the last cycle. The differences showed up just before failure, when a vertical displacement of 18 mm was applied: in TC11 the largest cracks were more spread along the height than in TC10, with the widest cracks near the base and top of the column (see Fig. 5e). While loading in compression, a large out-of-plane displacement towards East occurred: when the out-of-plane deformation was already significant, it seemed first to stabilize (out-of-plane displacement around 40 mm, see Fig. 4a), but then a sudden sound was heard—probably corresponding to an increase in crushing—and the out-of-plane displacement started to increase more sharply again, leading to the decision of stopping the test (see Fig. 5b).

The failure mechanism seems to consist of the development of four plastic hinges: two close to midheight at around 1000 and 1400 mm above the base (clearly visible in Fig. 4c), one at the base and one at the top. The plastic hinges can also be identified in Fig. 4c. The development of such a mechanism allowed TC11 to attain larger out-of-plane displacements in the cycles before failure in comparison with TC10 (see Fig. 4c).

3.3 TC12

Chronologically, specimen TC12 was the first to be tested and, because of a problem with the system controlling the servo-hydraulic actuator, the first tensile displacement applied was 3 mm instead of the planned 1.5 mm. Due to this unexpected tensile loading, the specimen immediately cracked along the entire height, with an average crack spacing roughly equal to the distance between the horizontal reinforcement (150 mm). In the initial loading protocol, the displacement increments between the cycles were larger: namely, the cycles with 9 mm and 15 mm of amplitude had been omitted. During the cycles at 12 mm the out-of-plane displacements were still very small, therefore they were followed by a tensile displacement of 24 mm (equivalent to a tensile strain of 0.01). At this load stage, the largest cracks were quite spread along the height. When the loading was reversed and the specimen loaded in compression, a very large out-of-plane deformation towards West occurred. The out-of-plane displacement attained at midheight was around 75 mm when loading was stopped. At this point, concrete crushing was observed at midheight and at the base of the column (see Fig. 5c).

The failure mechanism comprised four plastic hinges: one at the base and one at the top, and two almost at midheight at around 1000 and 1400 mm from the base (Fig. 4c). The deformed shape at failure of TC12 was therefore very similar to the one of TC11, although the out-of-plane displacement occurred towards East in one case and towards West in the other. In fact, these two specimens showed an overall mirrored behaviour throughout the test in terms of the side to which the deformation developed (Fig. 4a).

4. Analysis of the results

4.1 General observations

As discussed in the previous sections, the out-of-plane behaviour of the three specimens tested was quite similar, but although the geometry was the same and the loading protocols similar, a few differences in the responses can be pointed out.

The first difference relates to the side towards which the columns developed an out-of-plane deformation: (i) TC10 displaced towards East throughout the test and at failure, (ii) TC11 displaced towards East throughout the test and towards West at failure and (iii) TC12 displaced towards West throughout the test and towards East at failure. Since the geometry of the specimens was the same, the differences in behaviour might show that an eccentricity of 8 mm is too small to influence the side towards which the out-of-plane deformation will take place. Concerning the reproducibility of the tests, one can note a certain variability in the responses of the specimens, most probably related to the unstable character of the phenomenon and the almost symmetric properties of each column.

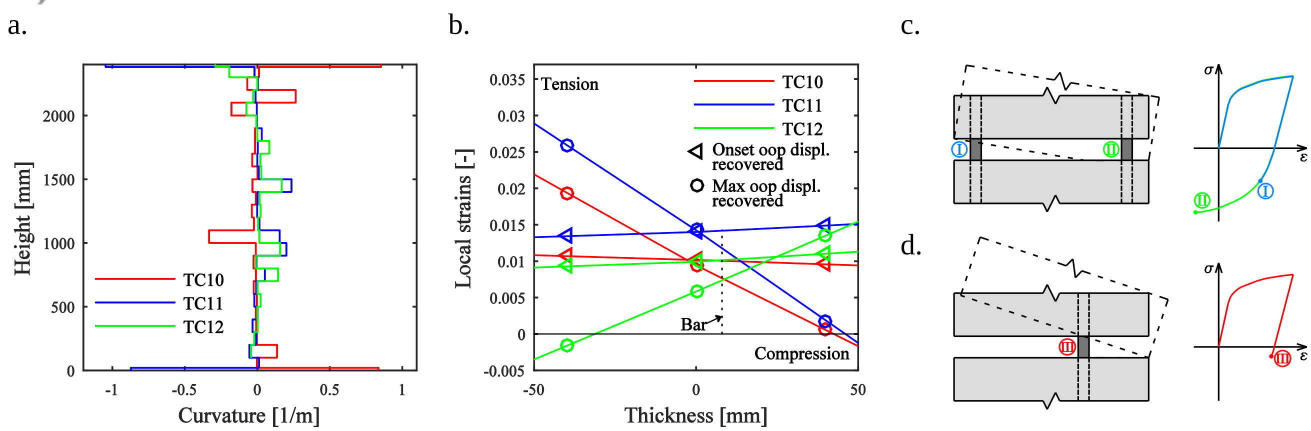

Fig. 6 – a. Curvature profiles along the height at an out-of-plane displacement of 30 mm; b. Strain profiles along the thickness at the height of the plastic hinges at onset of and at maximum out-of-plane (oop) displacement recovered; c.-d. Description of the onset of out-of-plane instability in case of one or two layers of reinforcement.

TC12 was subjected to fewer cycles than TC10 and TC11 since the cycles with amplitudes 1.5, 9, 15, and 18 mm had been skipped (Section 2.2). If one compares the out-of-plane displacement of all three test units after imposing for the first time a vertical displacement of 12 mm (equivalent to a tensile strain of 0.005) one can notice two key differences between TC12 and TC10-11: first, TC12 deformed towards the opposite side of TC10 and TC11, i.e., TC12 buckled in the opposite direction to the eccentricity of the bar (Fig. 4a). Second, the maximum recoverable out-of-plane displacement at midheight that was attained by TC12 was smaller than that of TC10 and TC11 (Fig. 4a). This could be related to the different buckling side and / or the different loading protocols applied. The crack lips of TC10 and TC11 might have been slightly damaged during the 9 mm cycles, leading therefore to slightly larger displacements in the 12 mm cycles (the 9 mm cycles had been skipped in the loading protocol of TC12).

Fig. 6a shows the curvature profiles along the height in the last cycle before failure at an out-of-plane displacement of 30 mm, representative of a deformation no longer recoverable. The plotted curvatures are consistent with the strain profiles along the thickness calculated as described in the next section (see Fig. 6b). The curvature profiles clearly show that the largest curvatures are concentrated at the heights where the plastic hinges formed.

4.2 Local behaviour

Fig. 6b shows the strain profiles through the wall thickness at the height of the plastic hinge at around midheight. The profiles are plotted for the last cycle in which the lateral deformation was still recovered and therefore namely at the onset of out-of-plane deformation (see triangle markers in Fig. 3c and Fig. 4a) and at maximum out-of-plane displacement (see circle markers in Fig. 3c and Fig. 4a). The strains were computed considering the rows of LEDs above and below the mentioned plastic hinges. Each row is formed by three LEDs—placed along the thickness at positions -40, 0 and 40 mm with respect to the centreline of the column—and the vertical distance between the rows is 100 mm, see Section 2. Subsequently, the three strain measures obtained were interpolated linearly two by two in order to obtain a continuous profile along the entire thickness. In those cases where not one but two hinges formed at around midheight (i.e., forTC11 and TC12), the profiles are reported for the hinge that led to the larger strains. It can be noted that at the onset of out-of-plane displacement in all three specimens the strains are still positive and quite large, although globally the columns have started to undergo compressive forces. Upon further loading, at maximum out-of-plane displacement the curvatures had increased and at one side of the thickness compressive strains developed, thus evidencing cracks closure.

Fig. 7 shows the evolution of the axial strains at the heights of the plastic hinges (one or two depending on the specimen) that formed at midheight *vs* out-of-plane displacement at midheight. Fig. 7a-b-c depicts the local strains at the bar position (i.e., at an eccentricity of 8 mm from the centreline) as obtained from the interpolation of the measured strains (see Fig. 6b). Note that the value of strain does not correspond to the actual strain in the steel within the crack, but to the average value of strain along the length between the two LEDs at the rebar position. The figure indicates that, for all the specimens, before the beginning of the out-of-plane deformation, a sort of elastic strain recovery takes place; the latter was approximately constant throughout the tests and took on a value of around 0.005 which was independent of how large the previous applied tensile displacement was. After this recovery, the strains remained almost constant whilst the out-of-plane displacements increased. Fig. 7d-e-f show the evolution of the strains on the edge along the thickness where the cracks first closed, i.e. the edge experiencing compressive strains at large out-of-plane deformations (see Fig. 6b). Comparing it with Fig. 7a-b-c, it can be noted that while the axial strains remain almost constant at the rebar position during the increase of out-of-plane deformations, the strains at the extremities change from tensile to compressive, corresponding to crack closure.

These observations may suggest that the mechanism of out-of-plane instability is somewhat different in members with one or two layers of longitudinal reinforcement. In fact, in a column with two layers of reinforcement—because of irregularities in the placement of the bars and/or of the variability in the position of the compression force—the layer of reinforcement closest to the compression resultant yields in compression (see green line in Fig. 6c). Only when the stiffness of this layer reduces significantly (due to the Bauschinger effect and plastification in compression), will large curvatures and correspondingly large out-of-plane displacements develop. The crack will eventually close on the edge adjacent to the first rebar yielding in compression, since the second bar has not yielded yet and hence retains a relatively large stiffness [5]. The development of this mechanism requires relatively large compressive forces in order to yield the first layer of reinforcement in compression, thus one can expect the onset of out-of-plane deformations for large compressive forces. On the other hand, in the case of a single layer placed eccentrically, as soon as the member undergoes compressive forces the reinforcement in the crack acts like a hinge around which the member parts above and below the crack rotate (see Fig. 6d). Therefore, the column can develop large curvatures at small values of compressive forces.

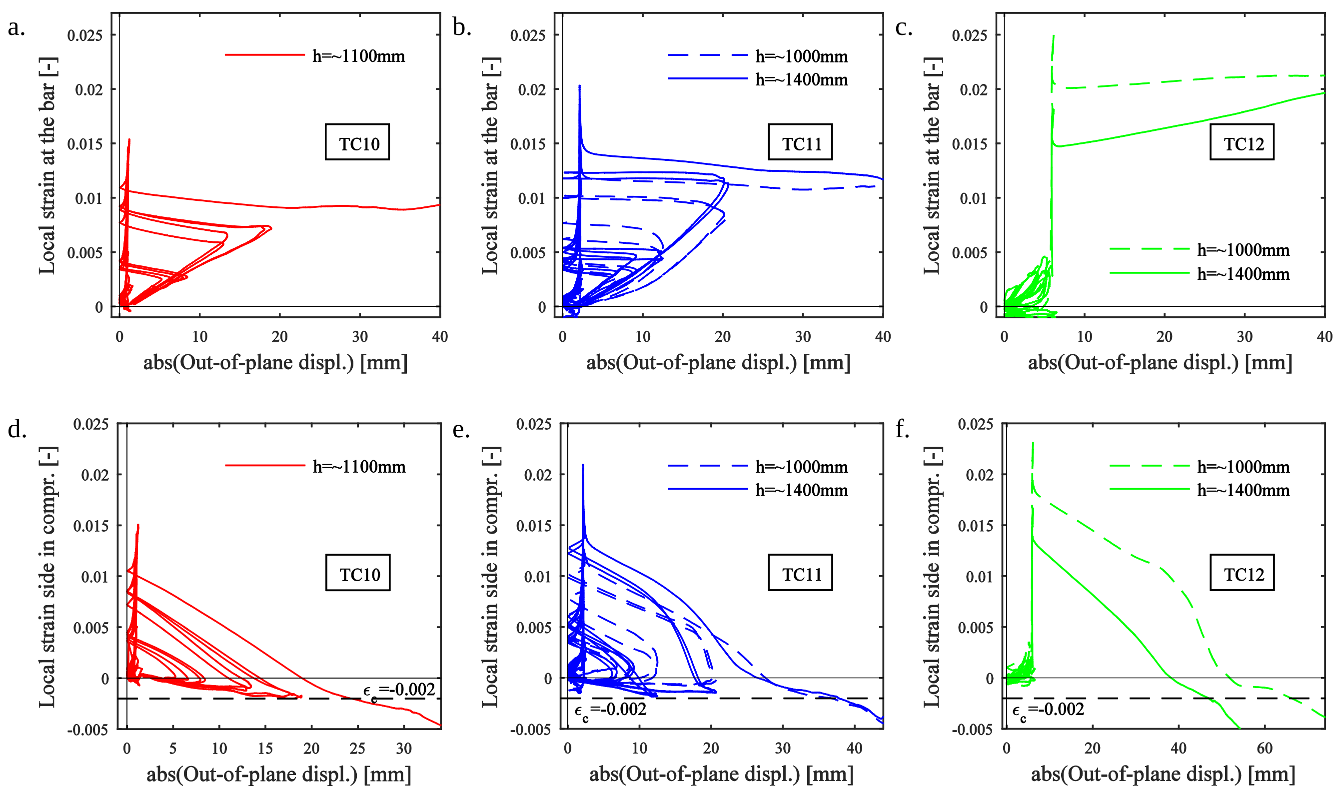

Fig. 7 – Local strain computed using the LEDs above and below the plastic hinges, a-b-c. at the rebar position in TC10, TC11 and TC12 respectively; d-e-f. at the edge that undergoes compressive strains in TC10, TC11 and TC12 respectively.

Fig. 7 shows that when the unloading starts, the 'local level' vertical strains are significantly larger than the global tensile strains imposed to the test unit; for example, in specimens TC10-11 the global tensile strain applied before failure was equivalent to 0.0075, while locally in Fig. 7a-b-d-e we can observe tensile strains approximately equal to 0.015 and 0.02 respectively. Moreover, Fig. 7d-e-f show consistently that a critical value of compressive strain equal to 0.002 is exceeded only in the last cycle, when the out-of-plane deformation is not recovered. This value usually represents the attainment of concrete compressive strength and onset of crushing. Although further investigation is required, the tests performed thus far show that attainment of local strains in compression larger than 0.002 seems to represent the critical condition defining out-of-plane failure or, in other words, of irrecoverable out-of-plane deformations.

5. Conclusions and future work

Many of the new residential buildings constructed in Latin America countries are built with very thin RC walls and a light amount of reinforcing steel. After the recent earthquakes in Chile (2010) and New Zealand (2011), it was found that thin RC walls are vulnerable to out-of-plane instability [1,2]. The existing models developed to describe the out-of-plane buckling of RC walls [5,6] approximate the boundary element—which represents the part of the wall mainly involved in the instability mechanism—by an equivalent column axially loaded in tension and compression. The loading parameter that governs the occurrence of out-of-plane deformations was identified as the maximum applied tensile strain prior to subsequent loading in compression. In order to investigate the effect of further parameters on the out-of-plane instability, the development of efficient modelling techniques and experimental investigation are required.

This paper presented the preliminary results of an experimental campaign that is carried out at École Polytechnique Fédérale de Lausanne, within a collaborative project with the University of Valle, EIA University and the University of Medellin, in Colombia. It comprises three cyclic axial-compression tests on thin RC columns with a single layer of vertical reinforcement, tested under cyclic tensile-compressive displacements. All three specimens showed large lateral deformations leading to member failure. The data collected allowed to get new insights into the development of the out-of-plane instability of columns with a single layer of reinforcement. Although further investigation is required, a few preliminary conclusions can be drawn:

(i) The onset of out-of-plane deformations always occurred when the column underwent low compressive forces.

(ii) All three specimens failed after having attained an average vertical tensile strain of 0.0075, corresponding to an applied vertical displacement of 18 mm (note that in TC12 the cycle at 18 mm was skipped, and hence the column failed after a vertical displacement of 21 mm). The last cycle in which the out-of-plane deformation was recovered corresponded to an average tensile strain of 0.005 for TC12 and 0.00625 for TC10-11. This suggests that the critical maximum tensile strain after which failure is attained lies between 0.00625 and 0.0075.

(iii) Although the geometry of the specimens was the same, the columns buckled to different sides. This suggests that the eccentricity of 8 mm was too small to influence the side towards which the out-of-plane deformations took place. Concerning the reproducibility of the tests, one can note a certain variability in the responses of the specimens, most probably related to the unstable character of the phenomenon and the almost symmetric properties of each column.

(iv) An analysis of the local axial strains at the height at which the plastic hinges formed showed that the single layer of reinforcement in the crack acts as a hinge around which the upper and lower parts rotate, suggesting that the instability mechanism is somewhat different than in members with two layers of reinforcement. Moreover, it was observed that a critical value of compressive strain equal to 0.002 was exceeded only in the last cycles when the out-of-plane failure was attained. Therefore, maximum section edge local strains in compression larger than 0.002 appears to represent the critical condition defining the attainment of out-of-plane failure.

The future experimental work comprises further nine column tests, which will investigate the influence of reinforcement ratio and of the eccentricity of the single layer of reinforcement with regard to the member axis.

Numerical simulations that can be easily used for design and assessment of thin wall to study the out-of-plane instability are under way [17].

6. Acknowledgements

The testing of the specimens is financed through an EPFL Seed Money grant through the EPFL Cooperation & Development Center, which was awarded to the EESD group (PI), the University of Valle, EIA University and the University of Medellin, in Colombia (Co-PIs). The first author is supported by the Swiss National Science Foundation. The third author participated to the biannual program 2015 between *EPFL* and *UniValle*, supported by *CODEV*, *VRI* and *ORI*. All contributions are gratefully acknowledged.

7. References

[1] Wallace, J.W., Massone, L.M., Bonelli, P., Dragovich, J., Lagos, R., Lüders, C. et al. (2012) Damage and Implications for Seismic Design of RC Structural Wall Buildings. *Earthquake Spectra*, **28**, S281–99.

[2] Sritharan, S., Beyer, K., Henry, R.S., Chai, Y.H., Kowalsky, H. and Bull, D. (2014) Understanding poor seismic performance of concrete walls and design implications. *Earthquake Spectra*, **30**, 307–34.

[3] Goodsir, W.J. (1985) The design of coupled frame-wall structures for seismic actions. PhD Thesis. University of Canterbury, Christchurch, New Zealand.

[4] Paulay, T. and Goodsir, W.J. (1985) The ductility of structural walls. *Bulletin of the New Zealand National Society for Earthquake Engineering*, **18**, 250–69.

[5] Paulay, T. and Priestley, M.J.N. (1993) Stability of ductile structural walls. *ACI Structural Journal*, **90**, 385–92.

[6] Chai, Y.H. and Elayer, D.T. (1999) Lateral stability of reinforced concrete columns under axial reversed cyclic tension and compression. *ACI Structural Journal*, **96**, 1–10.

[7] Oesterle, R.G., Fiorato, A.E., Johal, L.S., Carpenter, J.E., Russell, H.G. and Corley, W.G. (1976) Earthquake resistant structural walls - Tests of isolated walls. Rep. to Natl. Sci. Found. - Portl. Cem. Assoc. Skokie, Illinois, U.S.

[8] Thomsen, J.H. and Wallace, J.W. (1995) Displacement based design of reinforced concrete structural walls: an experimental investigation of walls with rectangular and t-shaped cross-sections. Rep. No. CU/CEE-95-06 - Dep. Civ. Environ. Eng. Clarkson University, Postdam, U.S.

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

[10] Almeida, J.P., Prodan, O., Rosso, A. and Beyer, K. (2016) Tests on thin reinforced concrete walls subjected to in-plane and out-of-plane cyclic loading. *Earthquake Spectra*, manuscript submitted.

[11] Rosso, A., Almeida, J.P. and Beyer, K. (2016) Stability of thin reinforced concrete walls under cyclic loads: state-of-the-art and new experimental findings. *Bulletin of Earthquake Engineering*, **14**, 455–84.

[12] Acevedo, C.E., Creagh, A., Moehle, J.P., Hassan, W. and Tanyeri, A.C. (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.

[13] Creagh, A., Acevedo, C., Moehle, J.P., Hassan, W. and Tanyeri, A.C. (2010) Seismic performance of concrete special boundary element. University of Texas at Austin and University of California Berkley, U.S.

[14] Chrysanidis, T.A. and Tegos, I.A. (2012) The influence of tension strain of wall ends to their resistance against lateral instability for low-reinforced concrete walls. *15th World Conference on Earthquake Engineering*, Lisboa, Portugal.

[15] Shea, M., Wallace, J.W. and Segura, C. (2013) Seismic performance of thin reinforced concrete shear wall boundaries. University of California Los Angeles, U.S.

[16] NDI. (2009) Optotrak Certus HD, Northern Digital Inc. [Internet]. http://www.ndigital.com/industrial/certushd.php, Waterloo, Ontario, Canada.

[17] Rosso, A., Almeida, J.P. and Beyer, K. (2017) Numerical simulation with fibre beam-column models of thin RC columns under cyclic tensile-compressive loading. *16th World Conference on Earthquake Engineering*, Santiago, Chile.