OUT-OF-PLANE INSTABILITY OF THIN SINGLE-LAYERED MEMBERS:
ADVANCEMENTS IN THE CHARACTERIZATION OF THE MECHANISM

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ABSTRACT

Out-of-plane instability of thin reinforced concrete walls under in-plane seismic actions is a failure mechanism that was observed after the earthquakes in Chile (2010) and New Zealand (2011). Past experimental campaigns carried out to study this phenomenon focussed almost exclusively on members where the longitudinal reinforcement is placed in two layers. However, recent experimental programs carried out at EPFL on single-layered reinforced concrete members allowed understanding important differences in the buckling mechanism of members with one and two layers of reinforcement. Advanced finite element models have been applied to study this particular type of instability, and the numerical results agree well with the experimental ones both in terms of global and local response parameters. Past experimental effort identified the maximum tensile strain experienced by the boundary element of the wall as the governing parameter triggering the out-of-plane instability. The existing phenomenological models are based on approximating the wall boundary element as an isolated prism subjected to tensile-compressive loading. Findings obtained from tests and numerical simulation showed that this approximation, although useful for understanding the mechanism, leads to rather poor predictions of the critical tensile strain triggering out-of-plane failure in walls. This paper presents the recent advancements in the characterization of the out-of-plane instability of single-layered reinforced concrete members, highlighting the main results of two experimental programs and of the finite element simulations. On the basis of the latter, an improved boundary element model is presented and its capacity to provide more accurate predictions of the wall behaviour is demonstrated.

Keywords: Out-of-plane Instability; Thin Reinforced Concrete Walls; Single Layer of Reinforcement; Large-scale Experimental Programs; Finite-element Numerical Simulation.

1. INTRODUCTION

Recent earthquakes in Chile (2010) and New Zealand (2011) led to significant damage on reinforced concrete (RC) walls (Kam et al. 2011; Wallace et al. 2012). As engineering practice is well anchored in seismic design principles in both countries, classical failure modes such as shear failures were relatively rare. However, since the ground motions were rather strong, new failure modes surfaced (Sritharan et al. 2014). Some of the observed structural failures are not yet completely understood (NIST 2014; Sritharan et al. 2014). In particular, it was seen that lateral instability of several wall boundary regions led to wall failures, which corresponds to a buckling type of collapse previously observed primarily in laboratory tests (Oesterle et al. 1976; Goodsir 1985; Thomsen and Wallace 1995).

Thin walls with only one layer of reinforcement have been found to be particularly vulnerable to out-of-plane instability (Rosso et al. 2016). This is of interest because over the last few years, due to the high material costs, in several South American countries—such as Colombia, Peru, Ecuador and Mexico—many new residential buildings were constructed with thin walls and a light amount of reinforcing steel that is placed in a single layer. It should be underlined that in Colombia the wall thicknesses are as low as 8 cm, while in Chile and New Zealand the minimum wall thickness is nearly

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twice as large (15 cm). It is therefore to be feared that such thin walls may develop out-of-plane failures during a major earthquake.

The development of the out-of-plane mechanism was first described as follows (Goodsir 1985; Paulay and Priestley 1993): at large in-plane curvature demands the boundary element develops large tensile strains, which are accumulated in wide near-horizontal cracks leading to 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. Therefore, 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 the compression force 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 the concrete. This leads to an increase in stiffness and a straightening of the wall. Or the cracks may remain open adding to a continued increase of the out-of-plane displacements and eventual wall buckling failure. The initial models developed to describe the out-of-plane buckling of RC walls (Paulay and Priestley 1993; Chai and Elayer 1999) approximate the boundary region—which represents the part of the wall mainly involved in the instability mechanism—with a pinned-pinned column axially loaded in tension and compression. The parameter that governs the occurrence of out-of-plane deformations is the magnitude of the maximum applied tensile strain prior to subsequent loading in compression (Paulay and Priestley 1993).

The main aim of existing mechanical and numerical models is to determine the critical tensile strain triggering an out-of-plane failure ($\varepsilon_{\text{glob,cr}}$). This parameter is herein defined as the ratio between the vertical displacement to which the boundary element is subject and the storey height. The scope of this paper is to provide a comparison between experimental tests and numerical simulations of thin walls and isolated boundary elements, in order to understand if the usual assumption of studying the wall behaviour by modelling only the boundary element subjected to tensile-compressive loading is an acceptable approximation for determining the critical tensile strain.

Firstly, a brief review of two experimental campaigns on walls and isolated boundary elements, and finite element simulations of the latter, is presented. Then, an improved numerical boundary element model, in which a specific vertical displacement profile along the height is applied, is proposed and validated against numerical and experimental results.

2. EXPERIMENTAL PROGRAMS OF THIN SINGLE-LAYERED MEMBERS

2.1 Experimental program on thin walls

With the aim of getting new insights into the behaviour of thin walls with a single layer of reinforcement, two specimens representative of typical Colombian design practice were tested at the École Polytechnique Fédérale de Lausanne (EPFL) under uni- and bi-directional loading by Almeida et al. (2016). The 1:1 scale walls were 80 mm thick, 2.7 m long, and 2 m high, with a shear span of 10 m, and had a short flange on one boundary. The longitudinal and horizontal reinforcement of the wall consisted of a welded mesh of 6 mm diameter with a spacing of 200 mm. The boundary element was 300 mm long, where three additional rebars of diameter 16 mm were placed at an eccentricity with respect to the centreline of the section of 4 mm. In the following only specimen TW1, which was subjected to uni-directional loading along the web will be discussed.

The loading protocol applied to TW1 consisted of horizontal in-plane displacement cycles; the corresponding amplitudes were increased every other cycle. The test unit attained an in-plane failure after reaching large out-of-plane deformations, which developed when reversing the load direction after an in-plane drift of 1%. Using an optical measurement system (NDI 2009), the three-dimensional displacement field of the specimen was continuously recorded, allowing namely to derive the vertical strain distribution in the boundary element. In Figure 1a the in-plane force vs the global tensile strain experienced by the boundary element is plotted.
(a) Figure 1 Thin wall TW1: (a) global tensile strain experienced by the boundary element vs in-plane force; (b) specimen at maximum out-of-plane displacement attained and recovered; (c) specimen at failure.

The average tensile strain in tension before failure is 1.3%. The buckling failure mechanism seemed to develop as follows: at 1% drift the web was in tension and all the cracks in the boundary element were open; when loading in the other direction, the crack width reduced but was still larger than zero. In the final cycle, first a large out-of-plane displacement developed (see Figure 1b), which had been partly recovered when crushing of the concrete and local buckling of the rebars in the lower part of the boundary element caused the failure of the wall and the end of the test (see Figure 1c). The wall crushed at its web toe (crushing had started in previous cycles), and was most likely partly caused by the out-of-plane deformations (Rosso et al. 2016).

Significant out-of-plane displacements were observed in the two cycles at 0.75% drift and just prior to failure. The onset of out-of-plane displacements (i.e., when a lateral displacement equal to 1% the wall thickness \((b)\) is attained, Rosso et al. 2017a) occurred for rather low compressive forces, as shown in Figure 1a. This feature distinguishes the response of members with a single layer of vertical reinforcement from the out-of-plane response of members with two layers of reinforcement, as it will be discussed more in detail in the next section. The current paper is based on three journal papers, which have either already been published or are currently under review (Rosso et al. 2016; Rosso et al. 2017a; Rosso et al. 2017b).

### 2.2 Experimental program on isolated boundary elements

To investigate further the out-of-plane instability of single-layered members, 12 thin RC columns (named ‘TC’), representative of wall boundary elements with a single layer of reinforcement, were subjected to axial tensile-compressive loads. The tests were performed at the same laboratory at EPFL. All the 1:1 scale specimens were 2.4 m tall and the cross-section was 300 mm long (refer to Figure 2). The longitudinal reinforcement was placed in a single layer, eccentrically with respect to the centreline of the section. The horizontal reinforcement consisted of 16 bars of 6 mm diameter, spaced of 150 mm. The column foundation and head were thicker and were designed to remain elastic. The loading protocol consisted of the application of cyclic axial displacements. The peak displacements in compression were the same throughout the loading protocol, while the peak displacements in tension were increased every other cycle.
Several parameters were varied between the 12 specimens in order to investigate their influence on the response. In the following only the behaviour of test unit TC02, which had the closest geometry to the boundary element of wall TW1, is discussed. The boundary element of wall TW1 and specimen TC02 had the same cross section (80 mm thick and 300 mm long), and differed only with regard to: (i) the interstorey height ($h_{tot}$), 2 m in the wall and 2.4 m in the column; (ii) the eccentricity of the single layer of reinforcement, which was increased from 4 mm in the wall to 8 mm in the column; (iii) the spacing of the horizontal reinforcement, which was decreased from 200 mm to 150 mm. The material properties were also slightly different but comparable (e.g., the concrete compressive strengths were 28.8 and 23.7 MPa respectively).

As in the wall tests, an optical measurement system allowed to record the three-dimensional displacement field of the specimens. Figure 2a plots the axial force vs the global tensile strain imposed at the top of TC02. The column attained significant out-of-plane displacements (see Figure 2b), and failed due to out-of-plane instability (see Figure 2c). This failure mechanism was associated with concrete crushing in the cracks closing first. As a result, the lateral deformation could not be recovered when the compressive force was increased further and the axial force capacity dropped (see Figure 2a).

More clearly than in the wall, it is observed that the onset of out-of-plane displacement (see Figure 2a) occurs almost immediately after the member starts to experience axial compressive forces, meaning that the rebars are obviously not yet yielding in compression (e.g., for specimen TC02 the axial force required to yield the reinforcement in compression is -317 kN but the out-of-plane displacements started to develop for a compression force as low as -8 kN kN, which corresponds to only 2.5% of the yield force). This feature of the response sets the behaviour of members with one layer of reinforcement apart from members with two layers. The reason has been found in the role that the longitudinal rebars play in the instability mechanism: in single-layered members, when loading from tension to compression, the reinforcement strains remain almost constant after reaching zero axial force whilst the out-of-plane displacement increases (Rosso et al. 2017a). This means that as soon as the member undergoes compressive forces, the reinforcement in the crack acts like a hinge around which the column regions above and below the crack rotate. As a result, the column can develop large localized curvatures at small
values of compressive forces. This observation suggests that the mechanism of out-of-plane instability is different from members with two layers of reinforcement, where the layer of reinforcement closest to the compression resultant needs to yield in compression before large curvatures and correspondingly large out-of-plane displacements can develop.

2.3 Comparison between boundary element and wall experimental response

The maximum attained tensile strains at failure are significantly smaller for the isolated column element TC02 than those in the boundary element of wall TW1, 0.50% vs 1.27%. This difference can be partially explained by the different storey heights. In fact, numerical evidence from wall modelling showed that an increase in storey height from 2 to 2.4 m may lead to a decrease of 18% in the critical strain (Rosso et al. 2017b). However, in the presented case the difference is much larger (39%) and other factors need to be considered when explaining the different responses, which will be shown later.

The global strains vs the out-of-plane displacements normalised to the thickness ($\xi_{oop}$) at the height where they were maximum (0.37$h_{tot}$ and 0.58$h_{tot}$ from the base for the wall and column respectively) are compared in Figure 3a. As discussed in Section 2.2, the wall did not fail due to pure global out-of-plane collapse as TC02, but an in-plane failure influenced by large out-of-plane deformations developed. The maximum out-of-plane displacement recovered by the wall is 0.58$b$, almost twice the maximum recovered by the isolated boundary element, equal to 0.32$b$.

Concerning the out-of-plane deformed shapes along the height, these are compared at the largest out-of-plane displacement recovered in Figure 3b. The profile of the wall is asymmetric, with larger displacements occurring towards the base. Differently, the isolated boundary element shape is more symmetric, with the maximum out-of-plane displacement attained around midheight.

Finally, the vertical displacement ($\Delta_y$) profiles along the height are compared in Figure 3c at maximum tensile strain attained, with a continuous line. These strains are the maximum experienced by the wall ($\varepsilon_{glob,\text{max}}$), and the critical triggering out-of-plane failure in the isolated boundary element ($\varepsilon_{glob,\text{cr}}$). While the vertical displacement profile of the isolated boundary element (not represented) is almost linear over the height, the vertical displacement profile of the wall assumes a bilinear shape. In fact, the profile might be approximated by the dashed-dotted lines represented in the figure. The kink in the wall profile has been identified to occur roughly at the height of the plastic hinge ($l_p$), which for instance in the presented case is 0.29$h_{tot}$. The concentration of the larger deformations at the base of the wall is related to the moment gradient effect, and it is also reflected in a different crack pattern, shown in Figure 4 at maximum tensile strain attained. The isolated boundary element presents a uniform crack distribution along the height, with the widest cracks located at the ends and close to midheight. On the contrary, in the wall the cracks tended to concentrate over the plastic hinge length, and the widest was detected just above the foundation.

![Figure 3](image_url)

Figure 3 Comparison of the experimental results of wall TW1 and isolated boundary element TC02: (a) global tensile strain vs out-of-plane displacement normalised to the thickness; (b) out-of-plane displacement profile along the height at maximum attained and recovered; (c) vertical displacement profile along the height at maximum tensile strain experienced.
3. NUMERICAL SIMULATION OF THIN SINGLE-LAYERED MEMBERS

The specimens described in the previous sections were simulated with a shell element model. The 3D finite element model was created in the software DIANA (2016) using curved shell elements that allow capturing buckling and post-buckling response phases. The models were adapted from the approach by Dashti et al. (2017). A four-node quadrilateral isoparametric curved shell element, named Q20SH, was used. The material behaviour is controlled at a grid of $11 \times 4$ (thickness $\times$ element plane) Gauss integration points. The reinforcement is modelled with embedded truss elements with two integration points. The compressive behaviour of the concrete is modelled using an uniaxial Hognestad parabolic curve (Vecchio and Collins 1993), while the tensile behaviour is represented as a linear tension softening. The ‘Total Strain Crack Model’ and the ‘Rotating Crack Model’ available in DIANA (2016) are employed. The steel behaviour follows the Monti-Nuti (1992) cyclic stress-strain law. A more detailed description of the finite element simulations can be found in Rosso et al. (2017b), where the models were extensively validated at the global and local level against the experimental results. In the following, only an overview of the comparison between the experimental and numerical results is shown, focusing on the aspects that are used later in Section 4.

3.1 Wall model

The wall model was subjected to the same in-plane loading protocol of TW1, and the experimental and numerical results are compared in Figure 5a in terms of global tensile strain in the boundary element vs normalised out-of-plane displacement. The first observation is that in the numerical model a different collapse mechanism develops, corresponding to an out-of-plane failure of the boundary element,
identifiable from the irrecoverable out-of-plane displacements, which occur in the last cycle. Comparing the out-of-plane displacements after a global tensile strain of 1% was attained, the latter is larger in the numerical model than in the test: 0.41b vs 0.33b. However, the maximum recovered in the simulation is still smaller than the maximum recovered by the specimen, equal to 0.58b. Then, after attaining 1.30% tensile strain, the test still recovers the deformation, while the model attains out-of-plane failure.

An extensive validation of the global behaviour in Rosso et al. (2017b) showed that, apart from the collapse mechanism, the numerical model is capable overall to provide good predictions, even when the wall is subjected to different boundary conditions, e.g. bi-directional loading.

3.2 Boundary element model

In order to reproduce the experimental behaviour of the boundary elements, also numerical simulation of isolated members under axial cyclic loading were carried out. Numerical evidence showed that imposing a complete cyclic history or single tensile-compressive cycles yield approximately the same results (Rosso et al. 2017b). Therefore, the experimental results of TC02 are herein compared to two numerical models, which are subjected to the following tensile strains: (i) the largest tensile strain for which an out-of-plane deformation recovery still takes place upon unloading and reloading in compression; (ii) the smallest tensile strain for which an out-of-plane failure is attained upon unloading from tension and reloading in compression, thus corresponding to the critical tensile strain. The corresponding two global tensile strains obtained from the simulations are 0.46% and 0.48% respectively.

First off, it should be noted that the critical tensile strain obtained with the numerical model is very close to the experimental one, with a ratio of the predicted to observed strain equal to 0.960. However, the maximum out-of-plane displacement recovered by the specimen is slightly underestimated by the model. Figure 5b illustrates the out-of-plane displacement at the height where it was maximum vs the global tensile strain imposed to the member. The out-of-plane deformations, both in the experiments and in the numerical simulation, started occurring at similar values of applied global strain. The maximum displacement attained and recovered by the specimen was 0.31b, while in the numerical model it was 0.24b. Finally, a very similar behaviour before failure can be observed: in the last cycle, after the maximum out-of-plane displacement is reached, the deformation seems to start recovering, only to increase suddenly and lead to out-of-plane failure.

Not only the wall model but also the model of the isolated boundary element was extensively validated against experimental tests, showing the ability of reproducing the local phenomena and the main trends observed. In particular, the critical tensile strain triggering out-of-plane failure is in general quite well predicted (Rosso et al. 2017b).

Figure 5 Comparison between numerical and experimental results: global tensile strain vs out-of-plane displacement normalised to the thickness in the (a) wall and (b) boundary element. (c) Vertical displacement profile along the height at maximum tensile strain experienced.
3.3 Comparison between boundary element and wall model

As underlined in Section 2, the isolated boundary element attained out-of-plane failure after smaller tensile displacements than in the wall. Since the numerical models reproduce well the experimental behaviour, this trend is also found in the numerical simulations.

In order to omit the influence of the different storey heights (Section 2.3, 2 m in the wall and 2.4 m in the isolated boundary elements), an isolated boundary element numerical model with 2 m height and the same material properties of TW1 was analysed. A critical tensile strain causing out-of-plane failure of 0.67% is obtained. Although the difference to the critical tensile strain of the wall reduced slightly (1.30% in the numerical model), it remains significant. In the following, it is shown that the main reason for the different critical tensile strains of the isolated boundary element and the wall boundary element is the different vertical displacement profile.

The vertical displacement profiles along the height are plotted at maximum tension (ε_{glob,max}) experienced by the boundary element in Figure 5c. The linear and bilinear shapes, of the isolated boundary element and the wall respectively, are even more evident in the numerical simulations. In the following, this finding is used to propose an improved numerical model of an isolated boundary element in which a bilinear displacement profile is imposed.

Note that in Rosso et al. (2017b) different modelling methods were applied and discussed, for instance considering the idealisation by Paulay and Priestley (1993) discussed in Section 1, which assumes the boundary element as pinned at the ends and with a height equal to the plastic hinge length. However, also under these conditions a significant underestimation of the wall critical tensile is obtained, showing the need of new approaches.

4. IMPROVED BOUNDARY ELEMENT MODEL

4.1 Vertical displacement profile along the height derived a priori

The proposed vertical displacement profile is assumed to be linear during the elastic phase of the in-plane response. In the inelastic phase, when the longitudinal reinforcement of a wall would yield over the height of the plastic hinge, the profile is assumed to be bilinear (Rosso et al. 2017b). The height at which there is a kink in the vertical displacement profile is assumed to correspond to the plastic hinge height, which can be calculated as (Priestley et al. 2007):

\[
l_p = k \cdot L_s + 0.1 \cdot l_w \tag{1}
\]

where \( k = 0.2 \left( \frac{f_u}{f_y} - 1 \right) \leq 0.08 \), \( f_u \) and \( f_y \) are the ultimate and yield strength of the reinforcement, \( L_s \) is the shear span, and \( l_w \) is the length of the wall.

Following the theory by Marti (2013), the imposed displacement profile (\( \Delta_y \)) along the height (\( h \)) can be written as (Rosso et al. 2017b):

\[
\Delta_y(h) = \begin{cases} 
\Delta_{top} \cdot \frac{h}{h_{tot}} & \text{for } h \in [0,h_{tot}] \text{ if } \Delta_{top} \leq \Delta_{top}^* \\
\Delta_{top} \left( 1 - \frac{l_P}{h_{tot}} \right) \Delta_{top}^* \cdot \frac{h}{l_P} & \text{for } h \in \left[0, l_P \right] \\
\Delta_{top} \left( 1 - \frac{h}{h_{tot}} \right) \Delta_{top}^* & \text{for } h \in \left[l_P, h_{tot} \right]
\end{cases} \tag{2}
\]

where:

\[
\Delta_{top}^* = \frac{h_{tot}}{l_P} \left( \frac{f_y}{E_s} l_P - \frac{3}{8 \rho_{BE}} \cdot \frac{f_y}{E_s} l_P \right) \tag{3}
\]
where $E_s$ is the Young modulus of the reinforcement, $f_{ct}$ is the tensile strength of the concrete, and $\rho_{BE}$ is the reinforcement ratio of the boundary element. In the numerical simulation, the displacement profile is imposed by applying different nodal displacements along the height of the isolated boundary element. The unloading phase and then the reloading in compression is assumed to follow the same pattern (Rosso et al. 2017b).

### 4.2 Validation of the improved boundary element model

The boundary element of wall TW1 was subjected to the displacement profile derived a priori for increasing global top displacement until out-of-plane failure was attained. The critical tensile strain obtained with this approach is 1.16%, which is much closer to the one obtained for the whole wall (numerically: 1.30%, experimentally: 1.27%).

The vertical displacement profiles along the height at maximum tensile strain are compared in Figure 6a: Eq. (2) seems to provide a good match to the profiles observed in the wall test and model, even if the critical top displacement is slightly smaller.

The response of TW1, the wall model, and the improved boundary element (IBE) model are compared in Figure 6b, for the last two cycles, in terms of global tensile strain vs out-of-plane displacement normalised by the wall thickness. A rather satisfactory match is obtained.

Furthermore, Figure 6c plots the out-of-plane deformed shape at maximum recovered out-of-plane displacement: while the original boundary element developed necessarily an almost symmetric shape (see Figure 3b), the improved boundary element profile resembles very well the one observed in the wall.

![Figure 6](image.png)

**Figure 6** Comparison between the experimental results, the wall model and the improved boundary element (IBE) model: (a) vertical displacement profile along the height at maximum tensile strain experienced; (b) global tensile strain vs out-of-plane displacement normalised to the thickness; (c) out-of-plane displacement profile along the height at maximum attained and recovered.

<table>
<thead>
<tr>
<th>Element</th>
<th>Type</th>
<th>Critical tensile strain</th>
<th>Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall</td>
<td>Experimental b</td>
<td>1.27% a</td>
<td>-</td>
</tr>
<tr>
<td>Wall</td>
<td>Numerical b</td>
<td>1.30%</td>
<td>1.02</td>
</tr>
<tr>
<td>BE</td>
<td>Experimental c</td>
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<td>0.39</td>
</tr>
<tr>
<td>BE</td>
<td>Numerical c</td>
<td>0.48%</td>
<td>0.38</td>
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<td>BE</td>
<td>Numerical b</td>
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<td>0.51</td>
</tr>
<tr>
<td>IBE</td>
<td>Numerical b</td>
<td>1.16%</td>
<td>0.91</td>
</tr>
</tbody>
</table>

*aConsidered as $\varepsilon_{glob,ref}$; note that since the test unit did not fail due to global out-of-plane instability, $\varepsilon_{glob,ref}$ does not represent the critical tensile strain in the test. bStorey height: 2 m. cStorey height: 2.4 m.*
In Rosso et al. (2017b) further validations of this approach are included, illustrating how the most important phenomena and trends are better captured in comparison with more classical approaches. An overview of the experimental and numerical results presented in this work is shown in Table 1. Clearly, the improved boundary element leads to a better approximation of the wall behaviour in comparison to the more classical boundary element models. Although the wall model corresponds to the simulation that gives better estimates of the wall behaviour, the improved boundary element model has the advantage of being less time consuming to implement and analyse.

5. CONCLUSIONS

The out-of-plane instability of thin reinforced concrete walls is a deformation/failure mechanism observed rather recently and of growing importance in view of new construction practices in some countries. The current work presents results of investigations on this subject, in particular with respect to members with a single layer of reinforcement. The following points were presented:
(i) An experimental test on a thin reinforced concrete wall (TW1) with a single layer of reinforcement. After attaining large out-of-plane deformations, the wall failed due to an in-plane collapse influenced by out-of-plane deformations.
(ii) Classical approaches in literature approximate the wall boundary element to equivalent prisms axially loaded in tension and compression. A specimen with characteristics similar to the boundary element of TW1, tested under cyclic axial loading, attained failure for a critical tensile strain much smaller than the one observed in the wall.
(iii) Numerical simulations of the wall and isolated boundary element were shown to reproduce quite well the experimental behaviours. However, also from the numerical viewpoint the boundary element approximation leads to an underestimation of the wall critical strain.
(iv) The main difference identified between the isolated boundary element and the wall behaviour consists of the applied vertical displacement profile along the height: linear in the former case, bilinear with a concentration of the strains over the plastic hinge height in the latter.

Finally, a proposal on how the vertical displacement profile along the height can be approximated is presented. When the isolated boundary element is subjected to such a displacement profile, the match with the wall critical tensile strain improved significantly, showing the potential of such a simple tool to assess quickly the vulnerability of a thin wall to out-of-plane instability.

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