EXPERIMENTAL RESPONSE OF T-SHAPE RC WALLS - EFFECT OF CONFINEMENT AND DISCONTINUITY

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ABSTRACT

The present paper describes a set of three T-shaped reinforced concrete (RC) walls tested under pseudo static cyclic loads. The T-Walls are designed and built to scale, in order to represent the characteristics (dimension ratios, reinforcement ratio, percentage of confined at the boundary elements) that are present in most Chilean’s buildings. The differences introduced between the three walls (confinement in the boundary elements and the discontinuity at the base of one of them), allow to study the effect of these characteristics in the distribution of strains, in the ductility and capacity of the T walls. Therefore, this investigation includes the description of the three walls, the experimental assembly and the analysis of the results. From the results, it is possible to observe the increase in ductility due to adequate confinement, but not a considerable increase in capacity in walls. On the other hand, the discontinuity generates a reduction in capacity and ductility, and a concentration of the plastic deformation at the level of the discontinuity, compared to the T-wall without discontinuity.

Keywords: T-Walls; Reinforced Concrete; Testing; Seismic Design; Instrumentation.

1. INTRODUCTION

The recent Mw 8.8-earthquake in 2010, revealed some problems in the design of reinforced concrete walls in different types of structures in Chile, and in particular in boundary elements of walls with sections like C, U or T. The failure modes observed, which had not been observed in previous earthquakes at Chile, were mainly due to a high level of flexo-compression and lack of confinement at the boundary elements. These caused the quick loss of concrete covering and the buckling in the longitudinal reinforcement (Massone, L., & Rojas, F. 2012). In addition, another characteristic of the majority affected walls were the discontinuities that these had at their base, responding mainly to architectural requirements, which caused an excessive stress concentration (Massone et al. 2017).

In addition, the importance of confinement in the global behavior and capacity in T-wall has been studied previously by Thomsen and Wallace (1995), and different investigations (Brueggen 2009, Brueggen et al. 2017) which have shown the relevance of experimental tests for the different criteria of construction and geometry in another countries. For example, experimental test of rectangular walls with discontinuities at their base were carried out in Chile prior to this study, where the concentration of strains in the area of the flag wall was observed (Manriquez et al. 2017). However, there is not experimental data for T-Wall with discontinuities at their base or for the Chilean characteristic of boundary elements pre and post 2010 earthquake.

In order to study the modes of failure observed during the 2010 earthquake, the effect of the discontinuities, and the effect of the new Chilean requirements for confinement of RC T-Walls, an
experimental research is carried out. In this experimental research, three specimens are tested under a quasi-static cyclic protocol with displacement control. The T-walls are at a scale about 1/3, with the geometry and reinforcement ratio corresponding to a residential building according to Chilean typical characteristics of construction before and after the 2010 Mw 8.8 earthquake. These tests were carried out in the Laboratory of Structures at the University of Chile. In the next section, the description of the T-wall, the experimental setup, and the results are presented.

2. DESCRIPTION OF TEST SPECIMENS

2.1 Geometry and Reinforcement

The dimensions and reinforcement ratio of the three specimens (ET1, ET2, and ET3) are based on a study of T-shaped walls in Chile, where real structures around of 18 stories and two basement are chosen, and studies their common characteristics (Silva 2016), which constitute examples of representatives building in Chile. Due to the limitations of space presents in the Laboratory, it is decided to carry out to scale the three specimens, that result in a height of 3.35[m], with 2.65 [m] corresponding to the wall itself, 0.4 [m] for the foundation that allows the embedment in the base and 0.3 [m] for the beam that allows the adequate transfer of the load. All test walls have a uniform thickness of 0.12 [m].

Walls ET1 and ET2 have a web of 120 [cm] and a flange length of 90 [cm]. However, Wall ET3, have a reduction of 20 [cm] in the edge of its web at the base level (Table 1). The aspect ratio between the length of the web and the height of the walls is 0.45, which defines a type of wall controlled mainly by flexion behavior. The longitudinal reinforcement ratio at the boundary element of the web is 2.5% ($d_b = 12$ mm), and for the edge of the flange and also at the intersection between the web and the flange is used 1.8% ($d_b = 10$ mm). On the other hand, the horizontal and vertical reinforcement consists of a double mesh with bars $d_b = 6$ mm at every 150 [mm], which gives a reinforcement ratio of 0.32%. It is important to note that the reinforcement of ET3 is identical to ET2. In Figure 1 the discontinuity stand out in blue, the slabs in light blue and the load transfer beam in yellow.

![Figure 1. Wall dimensions; a) 3D view; b) Plan View. (Unit: centimeters)](image_url)

It is important to emphasize, that the walls have the presence of 2 slabs, which confer additional rigidity to the walls, to be able to represent the present of slabs between floors. In addition, only walls ET2 and ET3 have confinement reinforcement with hoops of $d_b = 6$ [mm] at the boundary elements. A complete summary of the reinforcements is presented at Table 2 and also are shown in Figure 2.
Table 1. Dimensions of Walls.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ET1</th>
<th>ET2</th>
<th>ET3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall height [cm]</td>
<td>265</td>
<td>265</td>
<td>265</td>
</tr>
<tr>
<td>Web length $l_w$ [cm]</td>
<td>120</td>
<td>120</td>
<td>100</td>
</tr>
<tr>
<td>Flange length $l_f$ [cm]</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>$l_w / l_f$ [cm/cm]</td>
<td>1.33</td>
<td>1.33</td>
<td>1.11</td>
</tr>
<tr>
<td>Thickness [cm]</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 2. Reinforcement of Walls.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ET1</th>
<th>ET2</th>
<th>ET3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Web boundary reinforcement $4\phi12$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flange boundary reinforcement $4\phi10$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central reinforcement $16\phi6$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Confinement reinforcement $\phi6$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse spacing (hoops, vertical and horizontal reinforcement) [cm]</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
</tbody>
</table>

Figure 2. Details of reinforcement of ET1 and ET2. ET1 correspond to an unconfined configuration and the walls ET2 and ET3 correspond to the confined.

2.2 Materials

To characterize the materials, tests were carried out to the concrete and the reinforcement bars. In the case of the concrete, compression tests were done at 7, 14, 28 days and the day of the test of the respective wall, as well as simple tensile tests, using cylinders of 10[cm] in diameter to have the complete characterization of the concrete. For each of these tests there were 3 samples.

In the same way for steel, simple tensile tests were done for the rebar’s of $d_b = 6$, 10 and 12 [mm] and also cyclic tests for the bars $d_b = 12$ [mm], with a buckling ratio $L/d_b = 12.5$, that represent ET1 and
$L/d_b = 6.25$, that represent the separation between hoops and horizontal reinforcement presents at ET2 and ET3. Figure 3 shows examples of the experimental results and Tables 3, 4 shows the principal results obtained during the material tests.

### Table 3. Concrete compression and traction test.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ET1</th>
<th>ET2</th>
<th>ET3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f'_c$ [MPa]</td>
<td>31.6</td>
<td>35.6</td>
<td>24.8</td>
</tr>
<tr>
<td>$f''_c$ [MPa]</td>
<td>2.5</td>
<td>2.6</td>
<td>1.3</td>
</tr>
<tr>
<td>$e_c [-]$</td>
<td>0.027</td>
<td>0.026</td>
<td>0.020</td>
</tr>
</tbody>
</table>

$f'_c$: Peak compression concrete strength at the day of experimental test.
$f''_c$: Peak traction concrete strength at the day of experimental test.
$e_c$: Peak strain.

### Table 4. Tensile test for reinforcement of walls.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\phi 6$</th>
<th>$\phi 10$</th>
<th>$\phi 12$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_y$ [MPa]</td>
<td>460</td>
<td>430</td>
<td>440</td>
</tr>
<tr>
<td>$f_u$ [MPa]</td>
<td>855</td>
<td>738</td>
<td>768</td>
</tr>
</tbody>
</table>

$f_y$: Yield strength.
$f_u$: Ultimate tensile strength.

Figure 3. Examples of experimental results of materials. a) Tensile test for reinforcement bar $\phi 6$ and $\phi 12$. b) Concrete compression test of ET2 at the day of the wall test.

### 3. EXPERIMENTAL SETUP

The experimental setup and the testing protocol for the three walls are identical. The test setup is presented in Figure 4 and 5, which highlights the slab and reaction wall, the wall under study, the hydraulic jacks that apply lateral and axial load and the system of frame that restrict displacement out of the load plane. The walls are tested under a quasi-static cyclic protocol with displacement control, until reaching a 2% drift.
3.1 Instrumentation

All the walls tested were strongly instrumented to be able to obtain as much information as possible that allows to study and explain in the best way the phenomena that have occurred. Among the instruments used are LVDT's, Strain gages, Inclinometers and Load cells. In addition to this, the walls were monitored with 9 static cameras (0.08 pictures/seconds) to capture deformations and displacements using photogrammetry. The photographs allowed to detect in a more precise way the evolution of cracks and distribution of strain along the different faces of the wall. Finally, it is useful to point out that some measurements were made with Ultrasonic Sensors to try to correlate this type of non-destructive methods with the evolution of the damage in walls ET1 and ET3.
For each test, an arrangement of 48 LVDT’s was used (Figure 6), which were arranged to capture mainly the deformation in the first third of the wall, just under the first slab, where it is expected the majority of the deformation, cracks and strains are concentrated. In addition, two inclinometers are installed, one in the thickness of the web and one in the thickness of the flange (Figure 6), to be able to measure the angle with respect to the vertical of the first third of the wall outside the plane of the web, and the rotation of the flange.

In order to study the behavior of reinforcing bars, around 35 strain gages per wall were installed. The majority of these were located in the bars of the boundary elements, in the horizontal and vertical reinforcement, and hoops. Additionally, a strain gage was installed in a bar of the axial load system. Also, in ET3, two strain gages are installed to study also the overlap in the longitudinal bars in the area of the discontinuity.

In the test, two load cells are used, one to control the axial load and another one that is part of the hydraulic jack system that carries out the lateral displacement protocol, with a capacity of 100 [tonf].

Finally, 9 digital cameras (Canon: series T3i, T5i and T6), were installed to photograph globally and locally the flange and the web (Figure 7). The latter with the aim to studying the deformations and displacements with a digital image correlation process (DIC) with the NCorr software (Blaber et al. 2015).

The data processing of LVDTs, Strain gages, Load Cells and Inclinometers, are generated from continuous readings in voltage during the length of the tests. As for the cameras, a data structure is generated that has the processed displacements and deformations every 12 seconds. The use of conventional instrumentation and photogrammetry allows to contrast the results between the two methodologies and also complement the results to complete the study of the walls.
3.2 Loading Protocol

The test protocol consists of two parts. First, it is imposed the percentage of axial load that the walls should have and second, it is imposed the roof displacement on the load transfer beam. In relation to the axial load, a value of around \(0.085 f'_c A_g\) (where \(f'_c\) is the peak compressive concrete strength and \(A_g\) is the gross wall cross-sectional area) was initially estimated. The final values used are presented in Table 5. It is important to emphasize that the applied axial load correspond to an average load that is observed in Chilean buildings.
Table 5. Axial load ratio of walls.

<table>
<thead>
<tr>
<th></th>
<th>ET1</th>
<th>ET2</th>
<th>ET3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>9.5%</td>
<td>8.5%</td>
<td>12%</td>
</tr>
</tbody>
</table>

Now, in relation to the displacement protocol, this is based on the propose by ACI374.1 (2005), and it consists in pseudo static cyclic displacement that includes two drifts in the elastic range with subsequent drifts until reaching the global failure in the compressed area of the web. The point of application of the load is at 2.8 [m] from the slab and for each load drift there are 3 cycles. Figure 8 shows the protocol used, describing drifts in percentage and displacement in [mm].

4. EXPERIMENTAL RESULTS

4.1 Results ET1

Figure 9, shows the load-displacement curve for wall ET1, where a ductile behavior is observed for the direction when the flange is compress, but not for the direction when the web is compressed. It can be clearly seen that once the ET1 wall reaches its maximum capacity, suddenly reduced its capacity, due to crushing of the concrete and buckling of the bars.

The first cracks are observed at approximate drifts of 0.15 to 0.2%. For larger drifts, the cracks are mostly concentrated in the web, distributing mainly along two thirds of the wall. The spalling of concrete cover at the boundary element started in the last cycle of 1%. The strong drop observed at around 1.4% in the first cycle of 1.6% in the hysteresis corresponds to the spalling of all concrete cover exposing the entire reinforcement, which lead in the following displacements to the evident buckling of the longitudinal reinforcement. After this, it begins quickly to generate the fracture of rebar’s, ending all cycles of 1.6% with 4 bars ϕ12 fractured. This type of failure is the same as that observed in some Chilean buildings in 2010.

4.2 Results ET2

Figure 10, present the hysteretic behavior of the ET2 wall. In terms of capacity, shares the same characteristics of the ET1 wall (as expected), but a remarkable increase in the ductility compared to the observed in ET1. The spalling of concrete cover is started in the first cycle of 1.25% up to the height of the first hoop. The strong effect of the confinement is observed from this point, because the bars did not
show evident buckling until a large part of the concrete core in the boundary element was crushed due to large drifts.

From the 1.6% drift, a gradual damage of the entire wall was observed; the concrete cover is completely lost, leaving the reinforcing bars exposed. The cracks expand to the second floor and it is possible to observe some cracks in the slabs. Finally, the fractures of bars were generated at 2% drift, when the bars of the web were in tension, without significant damage to the flange, similar to the case of ET1.

![Figure 10. a) Load-displacement curve for ET2. b) Spalling of concrete cover at 1.6 %.

4.3 Results ET3

The load-displacement curve of the wall ET3 is presented in Figure 11. A similar behavior to wall ET2 is observed, in relation to the increase of the ductility. Despite the latter, it was observed a reduction in the capacity of the wall in the direction when the web was compressed, which could be attributed to the effect of the discontinuity, which produced a concentration of strains and stresses, because the length of web is smaller than the other walls. The spalling of concrete cover started in the first cycle of 1%. The boundary bars rapidly buckle for drifts of 1.6 % and after that the wall lose its capacity and it is observed a great damage accumulated in the height of the discontinuity (Figure 11 b). At the end of the test, the neutral axis was observed inside the flange.

![Figure 11. a) Load-displacement curve for ET3. b) Notorious damage in the whole web.](image)
4.4 Strain Measurements

In Figures 12, 13 and 14 are presented examples of strain measurements in web and flange (external side). Figure 12 present the strain distributions in the whole web in the first third of wall, for the drift of 1% when the flange was in compression (obtained from photogrammetry). These results indicates that the distribution of strains were concentrated in some cracks in height in wall ET1, instead, results of wall ET2 and ET3 (not present), the distribution was uniform in height, due to a good confinement at boundary elements.

![Strain ET1 - 1% Drift](image1)

![Strain ET2 - 1% Drift](image2)

Figure 12. Strain distribution obtained by photogrammetry. a) ET1. b) ET2.

Figure 13 and 14 show strain profiles along the entire web at the first 50 [mm] from the base of the wall ET1 and strain profiles in height for the edge of external side of flange, all measured with LVDT. Figure 13 present ET1’s results and Figure 14 ET2’s. It’s possible to observe higher compressions in wall ET1 than wall ET2 for the same level of drift. On the other hand, the behavior of flange is quiet identical, except for the fact that the boundary elements in wall ET1 has a greater demand, before the spalling of concrete, when the web was in compression.

![Strain Profile Web ET1 H=50[mm]](image3)

![Strain Profile of Flange in Height. X=850[mm] ET1 - Until 1%](image4)

Figure 13. a) Strain profiles along the web (ET1). b) Strain profile of flange at boundary element (ET1).
5. CONCLUSIONS

This work presents the results of a set of three T Walls with different configurations of reinforcement and geometry tested under cyclic loading. These tests are the first of their kind carried out in Chile, and with discontinuities in the world. This experimental research seeks to represent the reinforcement ratio and discontinuities representative of Chilean buildings, and in this way to be able to study the walls globally and locally, with the characteristic used in Chile before and after the Mw 8.8 2010 earthquake. From the results, it could be observed that the wall ET2, with a better confinement than ET1, presents an increase of at least 50% of ductility, which confirms why several structures in the 2010 earthquake had fragile failure in the boundary elements. It was observed that the absence of hoops and the way in which the transverse reinforcement was installed caused an excessive buckling.

On the other hand, the discontinuity in the wall ET3 generates a reduction in the capacity and ductility. It is also observed that the discontinuity generates a concentration of strains in the height of the discontinuity, which is attributed to the speed at which the spalling of concrete cover occurred. In the case of the flange of walls, this had a similar behavior in the three tests, which did not suffer spalling of concrete cover or buckling of bars, and showing a fairly ductile behavior.

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7. REFERENCES


