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

F. Muñoz¹, F. Rojas², L. M. Massone³, M. Ruiz⁴ and M. Silva⁵

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 maximum displacement 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 the maximum drift 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 displacement, and a concentration of the plastic deformation at the level of the discontinuity, compared to the T-wall without discontinuity.

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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 maximum displacement 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 the maximum displacement 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 displacement, and a concentration of the plastic deformation at the level of the discontinuity, compared to the T-wall without discontinuity.

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 [1]. 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 [2].

In addition, the importance of confinement in the global behavior and capacity in T-wall has

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been studied previously by Thomsen and Wallace [3], and different investigations [4], [5], 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 [6], 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 pre and post 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.

**Description of Test Specimens**

**Geometry and Reinforcement**

The dimensions and reinforcement ratio of the three specimens (ET1, ET2, 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 [7], 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] to a foundation that allows the embedment in the base and 0.3 [m] to a beam that allows the adequate transfer of the load (Fig 1.a). 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 (Fig. 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.
Figure 1. Walls dimensions. a) 3D view. b) Plan View. (Units: centimeters).

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.

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, Walls ET2 and ET3 have confinement reinforcement with hoops of \( d_b = 6 \) [mm]. A complete summary of the reinforcements is presented at Table 1 and also are shown (with geometry details) in Fig. 2 and 3. In Fig 1, the discontinuity (only ET3) stand out in blue, the slabs in light blue and the load transfer beam in yellow.
Table 1. 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</td>
<td>4φ12</td>
<td>4φ12</td>
<td>4φ12</td>
</tr>
<tr>
<td>Flange boundary reinforcement</td>
<td>4φ10</td>
<td>4φ10</td>
<td>4φ10</td>
</tr>
<tr>
<td>Central reinforcement</td>
<td>16φ6</td>
<td>16φ6</td>
<td>14φ6</td>
</tr>
<tr>
<td>Confinement reinforcement</td>
<td>-</td>
<td>φ6</td>
<td>φ6</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>

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. For each of these tests there were 3 samples. The peak compression concrete strength were 31.6, 35.6 and 24.8 MPa for walls ET1, ET2 and ET3 respectively.

In the same way for steel, simple tensile tests were done for the rebar’s of \( d_b = 6, 10 \text{ and } 12 \) [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. The yield strength and ultimate strength were around 440[MPa] and 750 [MPa]. Fig. 4 shows examples of the experimental results.
Figure 4. 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.

**Experimental Setup**

The experimental setup and the testing protocol for the three walls are identical. The test setup is presented in Fig. 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.

**Instrumentation**

All the walls tested were strongly instrumented. 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.

Figure 5. Setup Experimental for walls.
For each test, an arrangement of 46 LVDT’s was used (Fig. 6), which were arranged to capture mainly the deformation in the first third of the wall. In addition, two inclinometers are installed, one in the thickness of the web and one in the thickness of the flange (Fig. 6). 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. Finally, the 9 digital cameras (Canon: series T3i, T5i and T6), were installed with the aim to studying the deformations and displacements with a digital image correlation process (DIC) with the NCorr software [8].

![Figure 6. Instrumentation with LVDT's on Wall ET2 (web on the left and flange on the right)](image)

**Loading Protocol**

The test protocol consists of two parts. In relation to the axial load, a value of around $0.085 f'_c A_g$ (where $f'_c$ is the compressive concrete strength and $A_g$ is the gross wall cross-sectional area) was initially estimated. The final values used, are 9.5%, 8.5% and 12% for walls ET1, ET2 and ET3, respectively. It is important to emphasize that the applied axial load correspond to an average load that is observed in Chilean buildings. Now, in relation to the displacement protocol, this is based on what is proposed by ACI374.1 (2005) [9]. The point of application of the load is at 2.8 [m] from the slab and the reading of this is obtained through a load cell that is part of the hydraulic jack system. Fig. 7 shows the protocol used and the final setup of ET2.

![Figure 7. Experimental Loading Protocol and Setup Experimental at the beginning of the test.](image)
Experimental Results

Results ET1

Fig. 8 shows the load-displacement curve for wall ET1, where a ductile behavior is observed for the direction when the flange is compressed, 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 (Fig. 8 a). The spalling of concrete cover at the boundary element started in the last cycle of 1% (Fig. 8 b). 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 $\phi$12 fractured (Fig 8 c). This type of failure is the same as that observed in some Chilean buildings in 2010.

![Figure 8](image-url)

Figure 8. Load-displacement curve for ET1 and some pictures during the test.

Results ET2

Fig. 9 present the hysteretic behavior of the ET2 wall. The spalling of concrete cover is started in the first cycle of 1.25% up to the height of the first hoop (Fig. 9 b). 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, even in the flange (Fig. 9 a); 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 and all covering concrete was lost. (Fig. 9c)

Figure 9. Load-displacement curve for ET2 and some pictures during the test.

Results ET3

The load-displacement curve of the wall ET3 is presented in Fig. 10. A similar behavior to wall ET2 is observed, in relation to the increase of the maximum displacement. 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 higher concentration of strains and stresses (Fig 10 b, c). 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 (Fig 10 a).

Figure 10. Load-displacement curve for ET3 and some pictures during the test.
Comparisons of three specimens

Fig. 11 present a summary of the hysteretic behavior of T-wall. From these curves it is possible to observe the following points:

- The ET2, in terms of capacity, shares the same characteristics of the ET1 wall (as expected), but a remarkable increase in the maximum displacement, at least 30%.

- The behavior of flange is quiet identical for three walls (same capacity and maximum displacement), except for the fact that the boundary elements in wall ET1 has a greater demand later the spalling of concrete, when the web was in compression. The behavior is similar because the concrete in the compression zone in the flange was not damaged.

- It is important to note that the reduction on the capacity of ET3, it was not only due to the reduction of the length of the web, but also because the reduction on the capacity of the compression strength of the concrete used in ET3. A reduction of capacity is estimated around 20% using numerical models only for the effect of web’s reduction.

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 pre and post 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 maximum drift, 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 drift. 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 during the entire test.

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