EXPERIMENTAL STUDY OF FLEXURAL BEHAVIOR OF REINFORCED CONCRETE WALLS

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ABSTRACT

Design codes prescribe equations for ultimate state design of RC walls with flange walls as boundary elements considering part of the length of the flange wall as an effective width to resist lateral loads. However, the damage state and the accuracy of the effective width used in calculation have not been discussed. Therefore, loading test was carried out in Yokohama National University on two 1/3 scale specimens in order to evaluate the strength, damage state, energy dissipation and behavior of RC structural walls in flexure. One specimen without flange walls and one with flange walls were tested.
The strength and response of each specimen were described, and the prediction accuracy of the design flexural strength given by design codes ACI, Eurocode and AIJ was examined.
Experimental strain data was used to describe the behavior of the flange wall, in order to know the mechanism it develops when the in plane wall is loaded, and to confirm the accuracy of the effective width prescribed by design codes in tension and compression.
The result of the experimental study revealed that design prescriptions given by ACI, Eurocode and AIJ guidelines can estimate conservatively the flexural strength for RC walls without flanges, but they underestimate the flexural strength for flanged walls. This underestimation is due to the lack of knowledge of the mechanism developed at the flange.
It was not possible to determine a specific value of flexural effective width. However, it was confirmed that the flange width is underestimated by design codes and it increases with imposed drift level. The stress distribution at the flange in the out of plane direction was found not uniform, a fact that is different as the design assumptions.

Keywords: Flange Wall, Effective width, Flexural Strength.

1. INTRODUCTION

The use of Reinforced Concrete walls as structural element to resist the lateral loads imposed by earthquakes is a widely used system in countries prone to strong ground motion seismicity. Generally, reinforced concrete walls are called shear walls, because in the common case they resist the lateral load as a shear behavior element prior to flexural. When flange walls, are attached to structural in plane walls (web), they contribute to the lateral resistance. After 2010 Chile earthquake the importance to enhance the knowledge and design for flexural behavior of RC walls was evidenced. Several damages were caused in different buildings where the main resistant system consisted of RC walls without frames. The main objective of this study is to acquire knowledge of the behavior of RC walls in flexure, especially of the mechanism the flange walls develop. This is accomplished by analyzing the experimental results of a cyclic loading test conducted in Yokohama National University.

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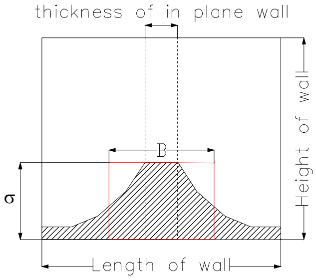

Figure2. Effective width of flange walls

In the case boundary elements are RC walls, the practice consists of considering the plane wall section as a beam with flanges, Figure 1. In this case the length of the flange wall that resist part of the moment caused by lateral load is called effective width.

It is possible to define the effective width according to the stress distribution in the flange wall. The stress distribute as shown in Figure 2, the stress σ_t, is the highest at the in-plane wall and it decreases going far from the center of the flange wall. The total force in the flange walls F can be calculated as the integral of the tensile stress for tension or compression.

The effective length "B" is given by Eq. (1), where t is the thickness of the web wall.

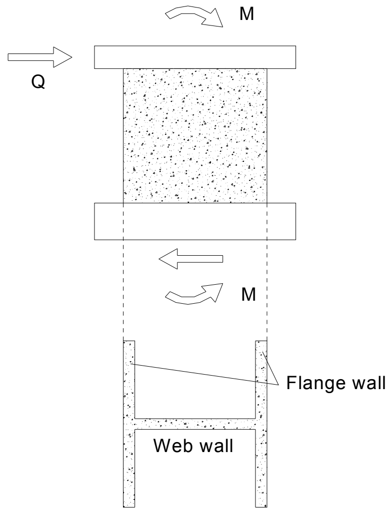

Figure1.Scheme of flanged walls

$$\sigma_t \times B \times t = F \qquad (1)$$

AIJ guideline uses the Eq. (2) for the calculation of flexural strength. ACI and Eurocode use a linear strain distribution using the concept of stress compression block at the concrete.

$${}_wM_u = a_t \cdot \sigma_{sy} \cdot l_w + 0.5 \sum \left(a_{wy} \cdot \sigma_{wy}\right) \cdot l_w + 0.5N \cdot l_w \qquad (2)$$

2. EXPERIMENTAL TEST

2.1 Overview of the specimens

The specimen N1 is a wall without flange walls at the ends and specimen N2 is a wall with flange walls in both ends in plane designed taking into account the effective width of the wall which is 6 times the thickness of the central wall, according to the AIJ Guidelines prescription. The reinforcement description and material properties for the concrete and steel are shown in Table 1 and Table 2 respectively. Plain view of each specimen is shown in Figure 3 and Figure 4. Specimens were intentionally designed to fail in flexural prior shear failure according to the provisions of AIJ Guidelines.

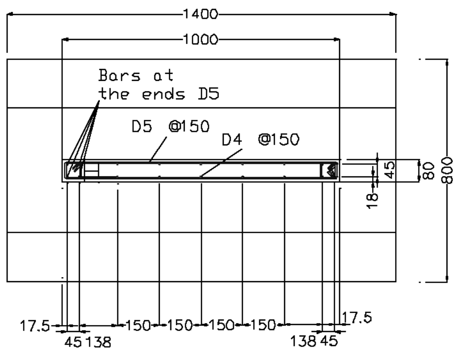

Figure 3.Plan view, specimen N1

Table 1. Dimensions and reinforcement arrangement

Description		Steel reinforcement				
		Thickness	vertical	Horizontal	At ends	Pwe (%)
N1	In-plane	80 mm	2-D4@150	2-D5@150	2-D5	0.37
N2	In-plane Flange	80 mm	2-D4@150	2-D5@150	2-D5	0.24

Table 2. Material properties

Concrete Properties	Young Modulus (MPa)	Tensile Stress (MPa)	Ultimate Stress (Mpa)	**Steel Properties (SD295)**	Young Modulus (MPa)	Yielding Stress (MPa)	Ultimate Stress (Mpa)
N1	$2.54X10^4$	2.48	31	D4	$1.85X10^5$	356	505.8
N2	$2.53X10^4$	2.26	31	D5	$1.92X10^5$	364	524.4

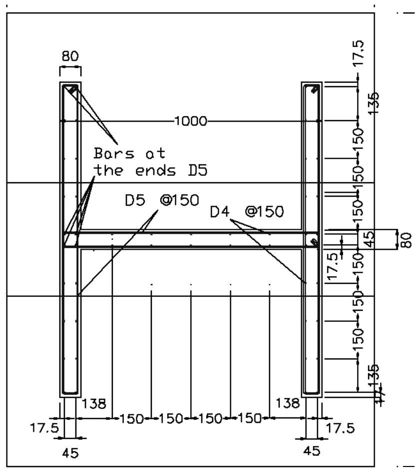

Figure 4.Plan view, specimen N2

2.2 *Load system*

Cyclic reversal lateral loading was applied statically to each specimen through one 1MN hydraulic jack. The load was transmitted by a rigid beam at the top of the wall and controlled by displacement at the same level. Figure 5 shows the applied loading system. Two 200 kN hydraulic jacks keep the vertical load in zero, so that the wall does not carry axial load.

The loading protocol consisted of the following drift target angles: ±1/6400, ±1/3200, ±1/1600, ±1/800, ±1/6400, ±1/400, ±1/200, ±1/100, ±1/66, ±1/50 and ±1/25. Positive direction is pushing toward to south. After ±1/800 each cycle is repeated once.

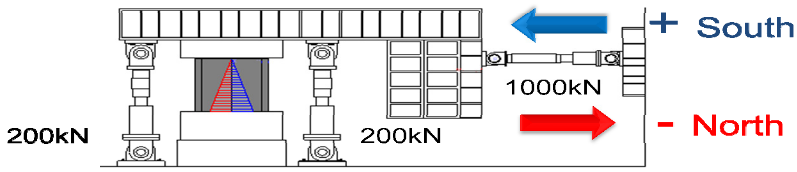

Figure 5. Load system

3. EXPERIMENTAL RESULTS AND ANALYSIS

3.1 *Specimen N1*

The first crack was observed at the drift angle of +1/3200 (R=+1/3200) at the north lower corner of the wall. This horizontal crack is a clear pattern of flexural behavior expected at the wall. And the same crack was observed at the south side when the load was directed to the opposite direction. At R= +1/1600 diagonal cracks appeared at the low north corner. The same pattern of diagonal cracks at the bottom of the wall developed in the following cycles in both directions appearing new ones going up to the height of the wall. Important cracks were measured from drift angle R=-1/800, at which the maximum crack width was 0.3 mm. The first reinforced bar yielded at the north side at R= +1/800 and at R= ±1/400 all the bars at the corners of the bottom of the wall yielded at load 58.6 kN f and 52 kN for positive and negative direction respectively. The maximum load was observed at R=±1/200. And it was 67 kN for the positive direction and 71kN for the negative direction. After this drift angle, the same crack pattern continued with the consequent growing of cracks. At R=± 1/100 sliding of the base of the wall occurred and at R=±1/50 compression failure was observed for the concrete at the lower corners with steel buckling, with cracks opened 5mm and 4.5 mm respectively. The wall resistance decreased slightly exhibiting ductile behavior. The specimen lost carrying capacity at R=2.5%.Thereafter, the test continued until R=+4.48%, when it was stopped because of the equipment limitation.

3.2 *Specimen N2*

In this test, small cracks were observed at R=+1/6400 at the south side in the intersection of the web and flange walls. At R= +1/1600, a horizontal crack appeared at the base of the north flange and similar crack developed at the base of the south flange at R=-1/1600. The maximum load of 150 kN occurred just before reaching the drift angle of R=+1/800, followed by the sudden formation of a diagonal crack extended from the north upper corner to the south lower corner of the wall and the sudden decrease of the restoring force. The diagonal crack at this drift was also extended to the north flange, and it measured the width of 0.85mm at the repetition of the loading cycle. Several diagonal cracks were developed after drift of R=1/400 in both directions and those cracks were also extended to the flange walls. At R=+ 1/100 the vertical reinforcing bars started to yield at the base of the corner of each side at a load of 124 kN. At the same stage, openings were measured at diagonal cracks with the maximum width of 5mm and 6mm at positive and negative peaks respectively. At R=1.20 %,(at cycle R=+1/66) most of the bars at the specimen yielded. After this step, the wall decreased its carrying capacity. The bigger crack opening was observed at the repetition of the load at the drift R=±1/50 and it was 18mm at the diagonal crack. The test stopped at R=2.10% because of the tensile failure of the vertical reinforcement bars occurred at the top of the north corner of the wall. This is attributed to the loading system, which consisted of a rigid beam, which causes concentration of stresses around the zone fixed to the wall. No compression failure of the concrete was observed during the test.

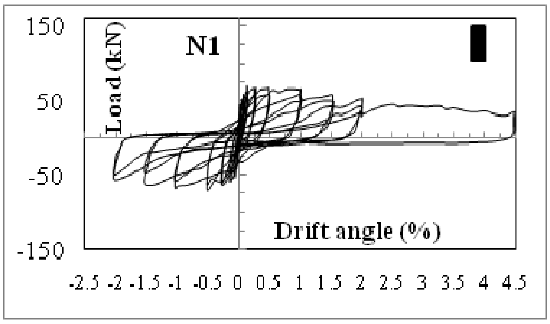

Figure 6. Load drift angle, specimen N1

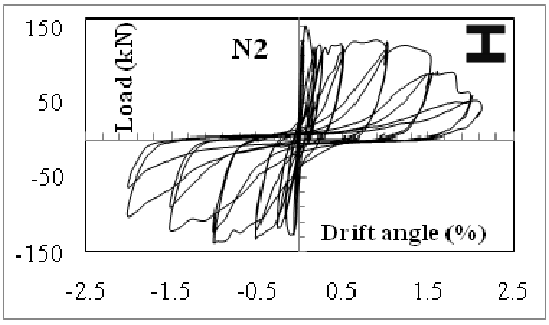

Figure7. Load drift angle, specimen N2

The skeleton curve and Energy Dissipation capacity is shown in Figure8 and Figure 9. The calculation methods used to estimate the flexural strength are: JBDPA-AIJ, ACI 318-08 and Eurocode2 (2004). Three cases are presented:

a) Flexural strength for specimen N1
b) Flexural strength for specimen N2, using each design code proposed effective width
c) Flexural strength for specimen N2, considering the complete flange is the effective width.

Table 3 and Table 4 show the result of the calculation compared with the values obtained from test for specimen N1 and N2 respectively in terms of the lateral force.

For the calculated values, the percentage respect to the force where all the reinforcing bars yieded is shown in parenthesis.

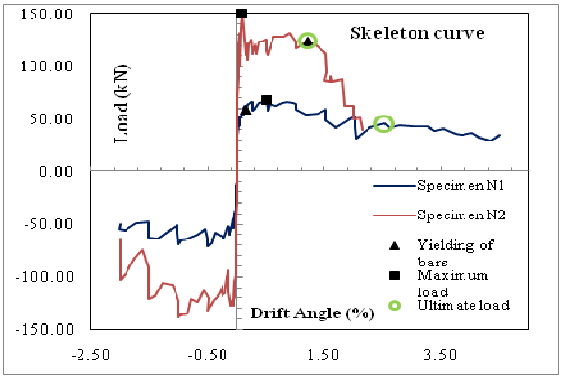

Figure 8. Skeleton curve

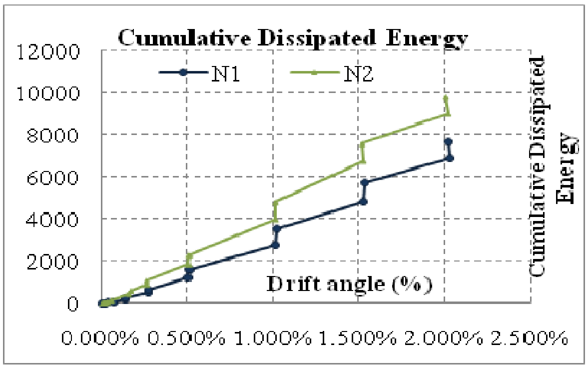

Figure 9. cumulative dissipated energy (kN mm)

Table 3. Ultimate flexural strength capacity, N1 (kN)

	Calculated			From test		
	AIJ	ACI	Eurocode	80 % Max	Yielding of bars	Ultimate Load
N1	52.4 (79.5%)	54.5 (82.7%)	54.4 (82.6%)	53.9	65.9 (R=0.25%)	45.4 (R=2.52%)

Table 4. Ultimate flexural strength capacity, N2 (kN)

	Calculated			From test		
	AIJ	ACI	Eurocode	80 % Max	Yielding of bars	Ultimate Load
N2	70.9 (57.2%)	76.2 (61.4%)	76.1 (61.4%)	119.9	124 (R=1.20%)	124 (R=1.20%)
N2 (total flange)	137.1 (110.6%)	147.5 (119%)	147.5 (119%)			

4. ESTIMATION OF EFFECTIVE WIDTH

The calculation of the effective width is performed for specimen N2 based on the basic concept presented in Figure 2 for both tension and compression. Using the strain history from strain gauges pasted at 90 of height from the bottom of the wall, the stress distribution can be obtained and with that stress, the value of the effective width “B” can be also obtained.

Effective width at the flange is calculated dividing the integral of the total area under the stress distribution by the value of the central stress. For the flange walls, lectures from the strain gauges pasted at the lowest section are taken from lines AA', BB', CC' and DD' at each peak of the Load-displacement. Figure 10 shows a plain view of the strain gauges distribution. When compression effective width is calculated, lectures taken by lines AA' and BB' come from the positive displacement peaks, and the lectures taken for lines CC' and DD' come from the negative displacement peaks. For tension the opposite convention is used. For compression effective width, the stress of concrete was calculated considering linear behavior of material, so that, the stress is given by the multiplication of the strain and young modulus of the concrete. Only strain data from layers AA' and DD were used in the calculation of compression effective width because it was determined that BB' and CC' carry tensile stress. For steel the stress was calculated with the strain history by the using of the bilinear model and young modulus and yielding forces as parameters for the model for all the layers.

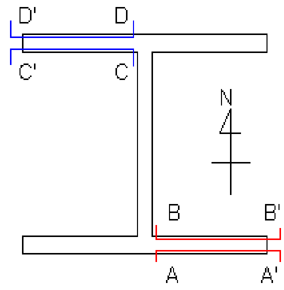

Figure 10. Plain view of specimen N2

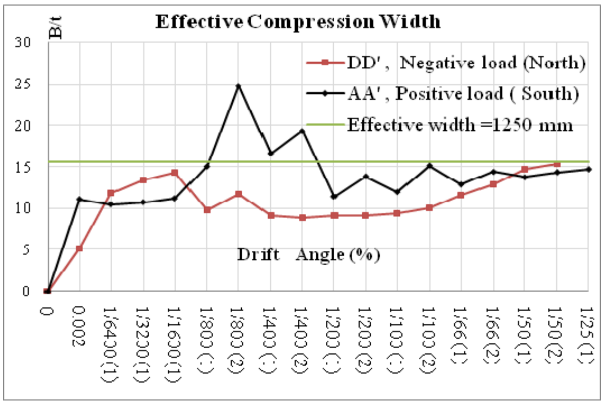

Figure 11. Effective tension width

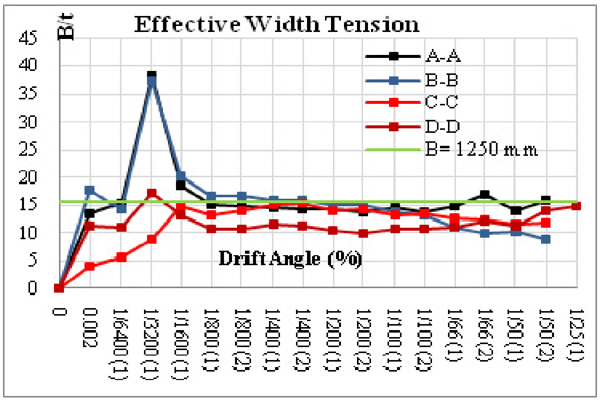

Figure 12. Effective compression width

Figure 11 and Figure 12 shows the variation of the calculated compression and tension effective width for this tested specimen respectively, where the length of the wall is 1250 mm. According to the curve corresponding to line AA' and BB' the values of effective width resulted from the calculation are larger than the real length of the flange wall. This is fact leads incongruence, because it implies the effective width is larger than the real length of the flange wall. It was determined that this result gives that trend because stress, according to stress distribution is not always the maximum at the center. Taking the lectures of the strain gauges pasted on the concrete the depth of the compression zone in plane was determined assuming a linear distribution of strain; the result is shown in Figure 13. According to this result it was impossible to calculate the effective width using the proposed method, and it implies the stress distribution in plane is not uniform at flange walls.

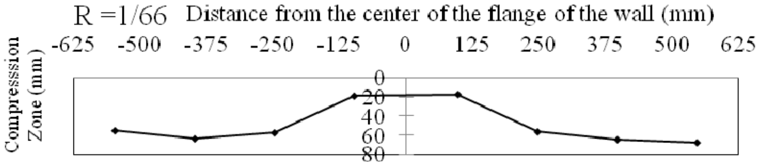

Figure 13. Compression zone at flanges in plain view

It is important to know not only the effective width of the flange wall, but the amount of reinforcing steel that was effective to resist tensile force. The total force carried by each flange was using the calculated stress values, and then the required area of steel at each drift angle is found.

The ratio between of the sum of the stresses of the flange wall and the yielding stress gives the equivalent number of yielded bars that resist the tensional force due to flexure moment.

The total area of steel is found by multiplying the equivalent number of bars, by the area of each steel bar. The result is expressed in terms of the yielding strength of bars D4. The calculated area of steel is expressed as the reinforcement ratio on the gross area of the wall and it means the amount of yielded reinforcement necessary to resist the tensile force in the flange at each peak of the loading test and it is shown in Figure 14. From the figure, it is noted that the amount of steel needed to resist the tensile force at the test is smaller than the reinforcement ratio provided by the whole flange. The maximum required reinforcement ratio is 0.32 % at the south flange that is also more than the correspondent value for the width "6 t".

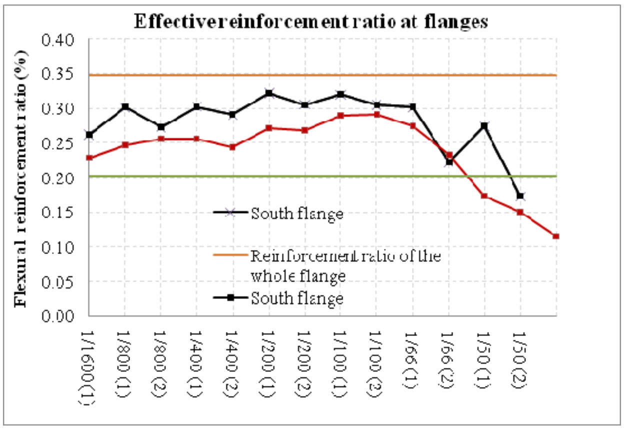

Figure 14. Effective reinforcement ratio

5. CONCLUSIONS

- Conventional methods to determine the ultimate flexural strength for RC walls predicted conservatively the flexural strengths observed for specimen without flanges but underestimated the flexural ultimate strength for flanged specimen.
- Specimen with flange walls showed larger energy dissipation capacity than specimen without flanges. However, specimen without flange walls presented larger and more stable value of equivalent viscous damping than flanged specimen.
- The calculation revealed that effective width is underestimated by design codes
- The test result suggests that stress distribution at the flange wall in the out of plane direction is not uniform.
- This experimental study confirms that the flange width increases with imposed drift level

6. RECOMMENDATION

Future test must be carried out to know the behavior of RC walls with flange walls as boundary elements, in order to confirm the results of this test. The combination of the axial and flexural behavior should be included and the dimensions of the wall should simulate continuous walls of more than one story, with larger slenderness ratio than the presented in this test, in order to reproduce the real scenario of RC walls in buildings

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