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Experimental evaluation of the seismic performance of reinforced concrete structural walls with different end configurations

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A B S T R A C T

The Canterbury Earthquake Royal Commission report (2013) showed that cantilever reinforced concrete (*RC*) walls failed at a lower ductility capacity than expected due to a plasticity concentration region within a very limited height near the location of the primary cracks at the base of the walls. The New Zealand Standards (*NZS 3101*) (2006) [2] and the Canadian design standards (*CSA A23.3-14*) (2014), adopt the same capacity design approaches for *RC* walls design, with both standards specifying a minimum vertical reinforcement ratios (ρ_v%) of 0.25% for *RC* walls. Subsequently, the current study was conducted to study the seismic performance of *RC* walls with different vertical reinforcement ratios and cross sectional configurations. In this paper, six half-scaled *RC* structural walls were constructed and tested under quasi-static displacement controlled cyclic loading. The walls had three different cross sectional configurations; rectangular, flanged and boundary elements and were tested with specific design characteristics selected to evaluate and compare the wall ductility capabilities. In this respect, wall ductility can be defined as the ability of the walls to undergo inelastic deformations with no/low strength degradation, which is essential in Seismic Force Resisting Systems (*SFRS*) as it is not economically feasible to design *SFRS* to behave elastically under seismic loadings. So the ductility quantification of the structural walls used were ductility ratio between the intended displacements with the yield displacement. Based on the test results, the ultimate drift at 20% ultimate strength degradation varied between 0.9% and 1.6% and the ultimate level displacement ductility ($\mu_{\Delta 0.8u}$), ranged approximately between 4.0 and 6.0. Although the flanged walls and the walls with boundary elements were designed to develop almost the same capacity as that of the rectangular walls, the seismic performance of the former wall type was found to be superior to that of their rectangular counterparts with respect to both the ultimate displacement capacity and ductility level. Moreover, using the flanges and the boundary elements walls resulted in approximately 30% reduction of the vertical reinforcement compared to that of the rectangular walls when designed to resist the same lateral loads while carrying identical gravity loads. In addition to gaining insights on the response of walls with boundary elements, the results indicated that structural walls with low vertical reinforcement ratio can experience reduced ductility as indicated in the Canterbury Commission Report.

1. Introduction

The Canterbury Earthquake Royal Commission report [1] revealed that some reinforced concrete walls that are designed according to the New Zealand Standards (NZS 3101) (2006) [2] and detailed to comprise the seismic force resisting system of buildings did not achieve their expected ductile capability. The report indicated that the reason was the formation of a primary flexural crack at the expected plastic hinge areas. Such crack might then keep increasing in size as the wall top displacements increase and consequently concentrating the steel plastic strain over a relatively very short height resulting in a premature wall failure at a much lower ductility level compared to what is expected. Such cracking pattern might result in strain concentration of the plastic hinge at a limited zone as well as limiting the generated energy dissipation during seismic event. The report showed that such less-than-expected ductile response was associated with insufficient vertical reinforcement that would have resulted in secondary cracks and higher energy dissipation. Consequently yielding of the

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Nomenclature

DS	damage state
f'_c	average compressive strengths of concreter cylinders
F_y	theoretical yield strength
h_w	wall height
l_w	wall length
$K_{0.8u}$	stiffness at 20% strength degradation
K_y	stiffness at yield
K_u	stiffness at the maximum load
MVLEM	Multiple Vertical Line Element Model
$Q_{0.8u}$	80% of the experimental maximum capacity
Q_y	experimental yield strength
Q_u	experimental maximum capacity
RC	reinforced concrete
R_d	ductility related response modification
SFI	Shear-Flexure Interaction
SFRS	Seismic Force Resisting System
Δ	target displacement level
$\Delta_{0.8u}$	ultimate level displacement at 20% strength degradation
Δ_y	yield displacement
Δ_u	displacement at the maximum capacity
$\mu_{\Delta 0.8u}$	displacement ductility at 20% strength degradation
μ_Δ	displacement ductility at the maximum capacity (Δ_u/Δ_y)
$\mu^{id}_{\Delta u}$	idealized displacement ductility at the maximum capacity
$\mu^{id}_{\Delta 0.8u}$	idealized displacement ductility at 20% strength degradation
ρ_h	ratio of steel reinforcement in the horizontal direction
ρ_v	ratio of steel reinforcement in the vertical direction

reinforcement was limited to the immediate vicinity of that single primary crack [1]. Subsequently, the report concluded with a recommendation to concentrate the vertical reinforcement ratio ρ_v, at the wall end regions to allow for the formation of secondary cracks and to enhance the energy dissipation capabilities by spreading the inelastic straining over a larger length of the outermost wall bars. Such detailing would then increase the wall plastic hinge height and hence, reduce the curvature ductility demands corresponding to different displacement ductility levels.

In addition, observations following the Maule earthquake in Chile (2010), indicated that structural walls showed deficient performance attributed to a combination of high axial loads and high out-of-plane slenderness ratios (small thickness) of the walls [4]. Moreover, Wallace et al. [5], concluded that the unexpected seismic performance in Maule Earthquake was due to the poor web boundary detailing where the strength degraded dramatically because of the buckling of the vertical reinforced after concrete crushing. Similarly, Carpenter et al. [6] concluded that the reason for the low ductile capacities of the structural walls in Maule Earthquake was the poor detailing and confinement. Most of the damaged walls were too thin to be confined which was considered another reason for the poor seismic performance of the structural walls in Maule Earthquake. Within the context of the current study, it might be argued that the small thickness of the walls reported herein was the common parameter between them and those that experienced low seismic performance during the Maule earthquake in Chile (2010).

Thomsen and Wallace [7] tested rectangular and T-shaped structural walls to examine the importance of confinement and transverse reinforcement spacing on the seismic performance of walls. It was concluded that small spacing of the transverse hoops could enhance the ductility of the structural walls. While Thomsen and Wallace [8] used the tested walls to analytically predict the strain profiles where the assumption of the plastic hinge $0.33l_w$ and $0.5l_w$ had a significant impact on the predicted results. Massone and Wallace [9] used the tested walls to assess the wall flexure and shear displacement contributions to the inelastic displacement. The study found that diagonally placed displacement transducer overestimate shear by up to 30% and that there is a strong coupling between inelastic flexural and inelastic shear deformations. Zhang and Zhihao [10] evaluated the seismic behavior of rectangular walls under high axial loading then concluded the negative effect of high axial loading on the walls ductility. Adebar et al. [11] tested *RC* core wall with high axial load and low vertical reinforcement ratio, in order to investigate the effect of cracking on the walls' effective stiffness. Concluded that although there were a large flexure and shear diagonal cracking in the wall, the effective stiffness of the cracked wall was similar to the uncracked wall due to the axial load. Sittipunt et al. [12] tested a series of *RC* walls to investigate the effect of diagonal web reinforcement on the hysteretic curves. They concluded that the diagonal web reinforcement enhance the walls energy dissipation and minimize pinching effect on the hysteretic curves. White [13] developed procedures to estimate the inelastic rotational demand of concrete walls, coupling beam chord rotation and the walls performance with axial yielding. They concluded that for higher period walls the axial demand of coupled walls decreased and walls allowed to yielding in axial tension showed lower coupling beam rotations and energy dissipation capacities.

Beyer et al. [14], tested U-Shaped structural walls in order to evaluate their flexural behavior in different directions. They concluded that the diagonal direction was the most critical direction where the displacement capacity was the smallest. Preti and Giuriani [15], tested a full-scale *RC* wall reinforced with unusual large rebar diameters, uniformly distributed along the wall length. The wall showed high ductility capacity, ensuring a uniform crack pattern and eliminating any localization of crack in the web region. Liao et al. [16], investigated the effect of reinforcing boundary elements walls with Structural steel section in the confined region, where the lateral load capacity increased but failure mode could only change from shear to a mixed flexure-shear mode when the aspect ratio (height/width) was three or more. Oh et al. [17] studied the effect of confinement and end-configurations of Reinforced Concrete structural walls, where they tested three rectangular and a barbell shaped walls. They concluded that the barbell and the well-confined rectangular wall showed similar ductility and energy dissipation.

Orakcal and Wallace [18] proposed a Multiple Vertical Line Element Model (*MVLEM*) to predict the flexural response of *RC* structural walls under cyclic loading. The model was designed to successfully capture *RC* walls cyclic response including the stiffness degradation, strength deterioration and hysteretic shape. Orakcal and Wallace [19] compared the *MVLEM* results with the experimental results and the model was capable of predicting the capacities, average rotations over the region of inelastic deformations, and neutral axis position. However, the *MVLEM* underestimated the compressive strains and was not accurate in predicting the non-linear tensile strain distributions in the flanges of T-shaped walls. Kolozvari et al. [20] proposed a model to accurately capture the nonlinear flexural/shear interaction of the cyclic