Engineering Structures 73 (2014) 13–23

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Effect of axial loads in the seismic behavior of reinforced concrete walls with unconfined wall boundaries

C. Alarcon, M.A. Hube *, J.C. de la Llera

Department of Structural and Geotechnical Engineering, Pontificia Universidad Católica de Chile, and National Research Center for Integrated Natural Disaster Management CONICYT/FONDAP/15110017, Vicuña Mackenna 4860, Santiago, Chile

ARTICLE INFO

Article history:
Received 21 August 2013
Revised 18 February 2014
Accepted 22 April 2014
Available online 22 May 2014

Keywords:
Reinforced concrete
Axial load
Wall
Experiment
Reinforcement buckling
Seismic behavior
Chile
Failure

ABSTRACT

About 2% of Reinforced Concrete (RC) buildings taller than nine stories suffered serious damage in structural walls during the 2010 Chile earthquake. The observed damage involved mostly crushing of concrete, buckling of vertical reinforcement, and opening of the horizontal reinforcement. This damage is attributed to poor concrete confinement in the web and boundaries, inadequate horizontal reinforcement detailing, and high axial loads. This research aims to reproduce the observed damage and evaluate the influence of axial loads in the seismic behavior of RC walls with unconfined boundaries. To achieve these objectives, three identical wall specimens were tested. The wall specimens were designed with characteristic wall detailing obtained from data of five damaged buildings. These wall specimens were tested under equal lateral displacement cycles and subjected to different axial load ratios. The flexural-compressive failure mode exhibited by damaged walls during the earthquake was reproduced in these tests. Experimental results indicate that high axial load has a significant effect on the seismic performance and failure mode of RC walls. Indeed, it triggers a dangerous brittle concrete crushing failure which occurs immediately after spalling of the concrete cover.

1. Introduction

On February 27th, 2010, the central south region of Chile was struck by an $M_w = 8.8$ earthquake [1], one of the strongest ever measured. More than 80,000 residences were destroyed and more than 100,000 suffered substantial damage caused by the earthquake and tsunami. The general performance of tall Reinforced Concrete (RC) wall buildings with 9 or more stories was acceptable; only about 2% of the newer building inventory presented severe damage [2,3] and just one of these buildings collapsed. This damage was most likely attributed to poor concrete confinement, inadequate horizontal reinforcement detailing, high axial loads, and low wall thickness [2,4,5]. Closed inspection to wall boundaries revealed lack of special boundary reinforcement, relatively large spacing of the horizontal web reinforcement, as well as 90° hooks in the horizontal reinforcement, which are inadequate for seismic detailing of RC walls [4].

Most of Chilean residential buildings rely on a structural system with a large number of RC walls to resist gravity and lateral loads. The ratio of wall cross sectional area to floor plan area in these buildings is about 3% in each direction [2,3]. The good building performance in the 1985 Chile earthquake was attributed to the high stiffness and strength provided by this structural system and it was concluded that confinement in RC walls was not required in such buildings [6]. However, after 1985, Chilean construction practice evolved, transforming these buildings into taller structures with thinner walls, which leads to an increase in axial loads and stresses. In many cases, buildings with 20 stories were built with 150–200 mm wall thicknesses and axial load ratios—ALR = N/f'_cA_g, where N is the axial load, f'_c the concrete compressive strength, and A_g the gross cross section of the wall—that could range from 0.20 to 0.50 [3]. The building survey performed by Jünemann et al. [2] indicates that most of damaged buildings in 2010 were mainly new structures constructed after year 2000 and that high axial load was a relevant factor that may have triggered the observed brittle damage.

In design, RC walls are intended to develop a ductile flexural behavior consistent with the strength reduction factor R, and hence, brittle modes of failure should be avoided. Hidalgo et al. [7] tested 26 squat walls in order to study the shear failure mode in Chilean RC walls. Because shear strength was the goal, these walls were tested conservatively without axial load to provide a lower bound of the shear strength, since ACI 318 [8] neglects this

* Corresponding author. Tel.: +56 2 2354 4207; fax: +56 2 2354 4243.
E-mail address: mhube@ing.puc.cl (M.A. Hube).

http://dx.doi.org/10.1016/j.engstruct.2014.04.047
0141-0296/

effect. The effect of high axial loads in the flexural behavior of RC walls was studied experimentally by Zhang and Wang [9] and Su and Wong [10]. They concluded that the axial load affects the cracking pattern, failure mode, and ductility of the walls. These conclusions were obtained by testing RC walls with transverse boundary reinforcement, which increases ductility by providing concrete confinement, which is not the case of Chilean walls. During a compressive failure of a well confined RC wall, the axial strength is not reduced after spalling of the cover concrete; the deformation capacity and strength of the concrete core increases due to confinement, and the inelasticity may be distributed along the wall height. However, if confinement is poor, damage in general will not be redistributed along the boundary element and may localize in a reduced region of the wall characterized by a brittle flexural-compressive failure, induced by crushing of concrete and buckling of vertical reinforcement bars as it was observed in some walls of damaged Chilean buildings (Fig. 1). This research aims to reproduce the damage observed in walls during the 2010 Earthquake and to experimentally evaluate the cyclic behavior of RC walls subjected to high ALRs. Findings from this project are intended to be considered in future RC walls design provisions in Chile in order to avoid the brittle failure mode observed in 2010. More details of this research project are available elsewhere [11]; experimental data is open to the community and will be available in the NEES Project Warehouse.

2. Survey of damaged buildings

A survey of critical walls of damaged RC buildings was conducted in this study to obtain representative characteristics of damaged walls. These characteristics were used to define a prototype wall for conducting the experimental campaign presented herein. General characteristics of five seriously damaged RC buildings and relevant properties of their walls were considered. Mostly, rectangular walls were included in this survey because their behavior is much simpler to interpret and hence experiments were limited to such sections as a first approximation to this complex problem; rectangular walls represent 32% of the total walls of the selected buildings.

Fig. 1. Typical flexural-compressive failure of RC walls during 2010 Chile Earthquake involving crushing of concrete, vertical reinforcement buckling, and horizontal reinforcement opening.

Five damaged buildings, whose number of stories ranged from 13 to 20, were considered in this survey. Four of them were located in the city of Concepción (CM, AH, PR and AA); whose characteristics were obtained from the survey performed by Westenenk et al. [12], and one in Santiago (EM). The specified concrete strength is $f'_c = 20$ MPa for PR and EM buildings, and $f'_c = 25$ MPa for CM, AH, and AA buildings. The wall characteristics considered in the survey were: wall thickness, M/Vl_w ratio (where M is the moment at the base of the wall, V the shear load and l_w the wall length), ALR, and reinforcement ratios. For this purpose, 27, 20, 14, 22 and 4 critical walls of the first two stories and basement–where damage was usually concentrated–were considered for CM, AH, PR, AA and EM buildings, respectively.

The wall thicknesses of the four buildings located in Concepción range between 150 and 200 mm, and between 170 and 250 mm for the EM building. The vertical loads and the M/Vl_w ratios were obtained from finite element models of the buildings using ETABS [13]. The moment (M) and the shear (V) of walls corresponds to the seismic demand obtained from a modal response spectrum analysis according to the Chilean Code [14]. The M/Vl_w ratio is an important property for the wall behavior, and if this ratio is small, the wall is considered squat and probably will exhibit a shear mode of failure [7]. The average of the mean M/Vl_w ratios of the critical walls in the damaged buildings is 2.02, which means that these walls cannot be considered squat, and hence flexural behavior is relevant. However, some of the selected walls in the buildings considered were squat with M/Vl_w ratios less than 0.5.

The ALRs of the surveyed walls of the five damaged buildings for gravitational load, including dead load and 25% of live load ($D + 0.25L$) are shown in Fig. 2(a) where the mean and standard deviation of the average ALRs for the five buildings is 0.18, and 0.10, respectively. The axial load in walls induced by an earthquake is estimated using modal response spectrum analysis according to NCh433 [14]. Fig. 2(b) shows the ALRs of walls of damaged buildings under gravitational plus earthquake loads ($D + 0.25L + E$), where the earthquake loads have been divided by the strength reduction factor. The mean and standard deviation of the average ALRs for the five buildings is 0.27 and 0.09, respectively. The mean average ALR for these loads is 50% larger than the value for gravitational loads. Also shown in Fig. 2(b) is the fact that about 10% of the walls are subjected to ALRs higher than 0.35, which is the limit imposed after the 2010 Chile Earthquake [15] for ultimate axial loads. Also, only 20% of the walls exhibit ALRs lower than 0.15 and the rest 70% of the walls exhibit ALRs between 0.15 and 0.35. This latter range of ALRs is considered for the experimental program of this research. However, if the load combination $1.2D + 1.0L + 1.4E$ is considered in this analysis according to NCh3171 [16], the mean of the average ALR of the five buildings increases to 0.38 and the percentage of walls with ALR higher than 0.35 increases to 37%.

The actual axial load demand in RC walls during the 2010 earthquake may have exceeded the one estimated from the design code. A comparison between the elastic response spectra, from the two ground motions recorded closest to the four buildings located in Concepción, and the elastic design spectra is shown in Fig. 3. The ordinates of elastic design spectra (S_{ae}) and response spectra at the fundamental period of the buildings are summarized in Table 1. The fundamental period of the buildings and the soil type, were