

Damage evaluation of lightly reinforced concrete walls in moment resisting frames under seismic loading

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ABSTRACT

An experiment was conducted on four lightly reinforced concrete (RC) wall specimens to study the effects of axial force, amount of shear reinforcement, and shear span to wall length ratio on their seismic behaviors such as load and displacement capacities, damage progress, and failure modes. The prototype specimens represented lightly RC walls, which suffered severe damage during the 2011 off the Pacific coast of Tohoku Earthquake. Shear type damage was observed for three specimens tested under double curvature. Increasing the amount of horizontal reinforcement and providing 180-degree hook anchorage reduced the development of shear cracking. A quantitative seismic damage evaluation in terms of crack width, crack length, and concrete spalling area was carried out to investigate the correlation between seismic damage and lateral drift. The damage level of walls was assessed using the 2004 Architectural Institute of Japan (AIJ) Guidelines, which takes into account the level of damage such as residual crack width or stress level of concrete and reinforcement. Considering the total amount of damage (crack length and spalling area), the criteria of the guidelines well captured damage level of lightly RC walls. In order to simulate the damage process as well as hysteresis curves of the tested specimens, finite element (FE) analysis was conducted. The analysis simulated the wall capacities with high accuracy and its crack distributions agreed well with the experiment for all specimens. Additional FE analysis with 210 case studies validated the design equations for flexure and shear capacities.

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1. Introduction

Masonry walls are generally used as infills in reinforced concrete (RC) frames in many countries [1,2]. In Japan, however, RC moment resisting-frames are usually constructed monolithically with lightly reinforced infill walls with opening (spandrels, wall piers, and wing walls). Although such walls are connected rigidly to the surrounding frame, structural engineers do not necessarily treat them as structural components [3] due to large openings and often neglect their contributions to the lateral load carrying capacities in practical structural designs. In the 2011 off the Pacific coast of Tohoku Earthquake, many lightly RC walls in residential and government office buildings suffered severe damage as shown

in Fig. 1 [4,5]. Such damage may not hinder the building safety but is likely to suspend the continuity of the building functions.

Many experimental tests have been conducted on RC shear walls [6,7], however, few tests have been performed to investigate seismic behaviors of lightly RC walls. Greifenhagen and Lestuzzi [8] carried out an experiment on one-third scale of four lightly RC walls by varying horizontal reinforcement, axial load, and concrete compressive strength to investigate their lateral load carrying capacities and deformation capacities. It was observed that lightly RC walls had large drift capacity, which was greater than or equal to 0.8%. They reported that the drift capacity was not affected by the ratio of horizontal reinforcement. The flexure strength governed the observed strength in the tests while ultimate drift was limited by shear failure. Two lightly RC walls were also tested by Gabreyohaness et al. [9] with plain round bars and no boundary elements with varying wall thickness and axial load of $0.05f_cA_g$ (where f_c is concrete compressive strength and A_g is gross cross-

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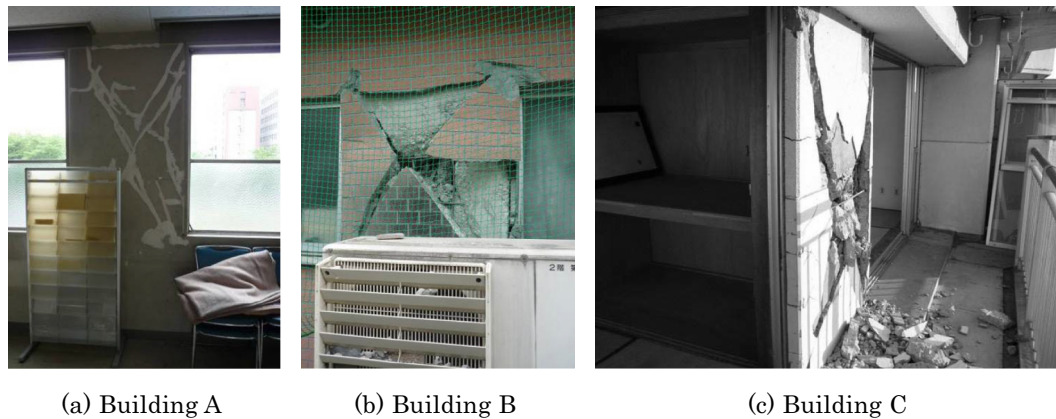


Fig. 1. Damage of RC non-structural walls after the 2011 Tohoku Earthquake.

sectional area of wall). It was found that the walls did not develop distributed flexure cracks but rather exhibited a predominantly rocking response about a single crack located at the foundation-wall interface. Orakcal et al. [10] evaluated the shear strength of lightly RC wall piers and spandrel by conducting an experiment on 3/4-scale of six wall piers and eight wall spandrel specimens. The test variables of this study were axial load (no axial force, $0.05f_c A_g$, $0.10f_c A_g$), shear span to wall length ratio (0.44 and 0.50), amount of longitudinal web reinforcement (0.227–0.428), and hooks on the transverse reinforcement. All specimens were tested under double curvature to represent the boundary conditions of an actual wall segment in a building. Lateral displacement of the wall piers was governed by shear deformations associated with diagonal cracking, followed by widening of and sliding along the diagonal cracks. Shear capacity of walls were compared with FEMA 356 and ACI 318-05. It was found that both FEMA 356 and ACI 318-05 gave a conservative shear capacity, especially for specimens with axial load of $0.05f_c A_g$ and $0.10f_c A_g$ since the formula does not consider the axial load.

Some researchers reported the effect of lightly RC wall on the seismic performance of RC moment resisting-frames in Japan. Sugiyama et al. [11] conducted an experiment on eight one-third scale of one-story one-span RC frame with cast-in-place lightly RC walls. The test parameters were types of openings in the lightly RC walls (two specimens) and strengthening methods with carbon fiber sheets on the lightly RC walls (six specimens). The axial load ($1/6f_c A_g$) was kept constant during the test for all specimens. Both two specimens without strengthening had higher initial stiffness and maximum lateral load capacity compared to frames without lightly RC walls. However, at 4% drift, their capacities were similar to those of specimens with wall failure. An experiment on three 1/2.5 scale RC frames with one story and one bay was carried out by Yoon et al. [12]. Two of the specimens had a lightly RC wall, which are monolithically constructed and structurally isolated by structural slits. Axial compression load of $0.1f_c A_g$ was applied to all specimens and maintained constant during the experiment. It was reported that lightly RC walls significantly affected the seismic performance of the overall frame, such as initial stiffness and maximum lateral load capacity. Furthermore, Sanada and Ojio [13] conducted 2D FE analysis on an 11-story steel reinforced concrete residential building in Sendai which was damaged at the 2011 off the Pacific coast of Tohoku Earthquake. The building was modeled with and without lightly RC walls to clarify their effects on the seismic performance of the building. It was concluded that typical lightly RC walls did not significantly affect seismic performance of a steel reinforced concrete building since lightly RC wall was damaged in early stage.

Although several studies have been conducted on the seismic performance of frames with lightly RC walls, no general method has been established to evaluate their seismic damages quantitatively. Since seismic performance of lightly RC wall is not clear yet, the damage level of building is often overestimated when the 2004 AIJ Guidelines [14] is used for assessment [13]. Therefore, further research is necessary to understand the behavior of lightly RC walls, in particularly focusing on their damage processes including failure modes.

This paper treats experimental studies on four lightly RC wall specimens to study the effects of axial force, amount of shear reinforcement, and shear span to wall length ratio on damage process. The main objective is to obtain fundamental data, such as damage state, load carrying capacity, and failure mode of lightly RC walls under seismic loading. The damage processes with ultimate failure mode are reported in detail. Damage evaluation in terms of crack width, crack length, and concrete spalling area was carried out at different drift levels to see damage progress of lightly RC walls. Then, the damage level was assessed using the 2004 AIJ Guidelines to study its validity for walls. In addition, a finite element (FE) analysis was conducted to simulate the hysteretic characteristic of lateral load – drift relations, evolution of damage, and to validate the design equations for flexure shear from 210 case studies.

2. Experimental program

2.1. Specimen description and materials

The test series included four specimens focusing on damage processes and failure modes of lightly RC walls as shown in Table 1. Fig. 2 shows configuration and reinforcement details of specimens. Experimental parameters were axial load, amount of shear reinforcement, and shear span to wall length ratio. The cross section of all specimens was 120 mm × 1050 mm with height of 2100 mm.

NSW1 and NSW2 were identical except axial load level. Two D13 reinforcing bars were provided as vertical reinforcement at the either end region, while D10 bars were used at 250 mm spacing as both vertical and horizontal reinforcement. NSW3 and NSW4 were identical except shear span to wall length ratio. They had double amount of horizontal reinforcement compared to that of NSW1 and NSW2. In addition, horizontal reinforcement of NSW3 and NSW4 had 180-degree hook anchorage at both ends as recommended by Mizutani et al. [15] to increase shear capacity and improve bond performance of longitudinal reinforcement. The measured mechanical properties of concrete and reinforcing bars are shown in Tables 2 and 3, respectively. All mechanical properties

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