ARTICLE IN PRESS

Engineering Structures 138 (2017) 1–15

Contents lists available at ScienceDirect

Engineering Structures

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

Experimental study of lightly reinforced concrete walls upgraded with various schemes under seismic loading

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A R T I C L E I N F O

Article history:
Received 20 September 2016
Revised 28 December 2016
Accepted 1 February 2017

Keywords:
Lightly RC wall
Shear failure
Upgrading
RC panel
UFC panel
Detailing

A B S T R A C T

The 2011 off the Pacific coast of Tohoku Earthquake clarified the weakness of lightly reinforced concrete (RC) walls with opening (spandrel, wall pier, wing wall) in residential and government office buildings. Lightly RC walls are not a critical structural component, but their damage often impaired functions of buildings after earthquakes although it did not jeopardize safety. In order to avoid the suspension of building function due damage to lightly RC walls, it is very important to have proper upgrading schemes to improve the seismic performance. An experimental study was carried out on three full-scale wall specimens upgraded with various schemes to improve the seismic behavior of shear-type damage of lightly RC walls. Two specimens were upgraded using additional RC panel and ultra-high strength fiber reinforced concrete (UFC) panel to prevent shear failure. The other specimen had upgraded reinforcement details to increase shear capacity and flexural ductility. The test results were compared with past lightly RC wall test as a reference wall, which failed prematurely in shear reproducing the failure observed in the field. The changes of ultimate failure mode and the damage process were observed. Three upgraded specimens showed ductile and stable behavior with less damage compared with the reference wall. Adding RC and UFC panels improved the behavior of lightly RC wall and prevented crack formation at the central part of the wall panel. Increasing the amount of horizontal reinforcement and providing confinement in the boundary regions controlled the opening of crack width and made structure more ductile.

1. Introduction

The National Institute for Land and Infrastructure Management (NILIM) and the Building Research Institute (BRI) reported that many perimeter lightly reinforced concrete (RC) walls with opening (spandrel, wall pier, wing wall) in residential and government office buildings had severe damage during the 2011 off the Pacific coast of Tohoku Earthquake [1] as shown in Fig. 1. Most damages to these walls were due to shear cracking or failure. Such damages did not affect safety of buildings but suspended the continuity of the building functions. In Japan, these walls are structurally connected to the surrounding beams or columns. They are not a primary structural component and are often treated as a secondary structural component which attract less attention in design [2]. A common design practice sometimes neglects their contributions to the lateral load carrying capacities. Lightly RC walls are typically 120–200 mm thick, and have a single curtain of reinforcement in two directions with a few additional boundary vertical reinforcing bars at section ends. In many cases, horizontal reinforcement has no hook anchorage and boundary region has no confinement. Hence, the current design practice makes lightly RC walls intrinsically vulnerable to earthquake damages. In order to avoid these damages, it is very important to have proper upgrading schemes to improve the seismic performance of lightly RC walls.

Many researchers have conducted experimental studies on upgraded RC walls using different techniques and materials. These retrofitting techniques aim to improve the wall strength, stiffness, ductility, or a combination of them. One of the most frequently used methods for strengthening of RC members is the RC jacketing. The effect of strengthening brick and block masonry walls by RC

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http://dx.doi.org/10.1016/j.engstruct.2017.02.005

Please cite this article in press as: Yuniarsyah E et al. Experimental study of lightly reinforced concrete walls upgraded with various schemes under seismic loading. Eng Struct (2017), http://dx.doi.org/10.1016/j.engstruct.2017.02.005

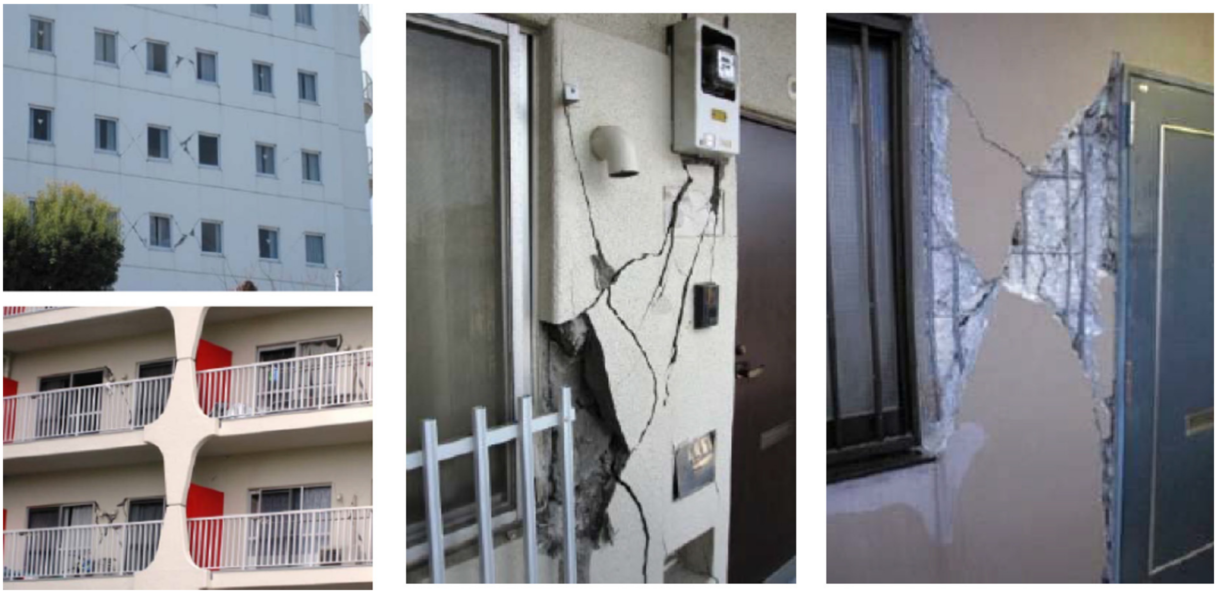

Fig. 1. Damage of lightly RC walls after the 2011 Tohoku Earthquake.

jacketing has been experimentally investigated in many cases [3–6]. The experiments showed that RC jacketing improves the lateral capacity. However, only few experimental works have been performed using this technique for RC walls. Marini and Meda [7] carried out an experiment on a one-third scale of RC shear wall retrofitted using high performance concrete jacket to improve its seismic behavior. The specimen represented a typical RC wall of an existing three-story building designed only for gravity load. The wall was 3.2 m high and its cross section was 100 mm × 800 mm. A 15 mm concrete jacket thickness with $\phi 2$ high strength steel mesh embedded was used as retrofitting materials. It was observed that the structural behavior was governed by flexure up to collapse with no appreciable influence of the shear effects. The strengthened wall failed due to crushing of concrete jacket at the base, exhibiting high ultimate strength and deformation capacities. In order to investigate the hysteresis behavior of shear deficient RC walls strengthened by bonding of steel strips, Altin et al. [8] tested four half-scale shear walls. The specimens consisted of one reference wall and three strengthened walls using externally bonded steel strips with different configurations. To prevent debonding and delay premature buckling of steel strips, an epoxy adhesive was applied to the surface of the wall with some anchor rods. All strip combinations improved the hysteresis behavior of the shear deficient RC walls significantly under cyclic loads. Strengthened specimens developed their nominal flexure strength, and hence, the observed maximum shear was controlled by flexure. The diagonal tension shear capacity of the wall was significantly enhanced by this strengthening technique. The strengthened wall exhibited 65% higher maximum strength than the reference wall, with improved initial stiffness and ductility. Liao et al. [9] conducted an experimental test on three low-rise shear walls with shape memory alloy (SMA) bars as a kind of structural bracing system to improve the seismic behavior of low-rise shear walls. The height, width, and thickness of the specimens were 1000 mm, 2000 mm, and 120 mm, respectively. The SMA bars were inclined at an angle 27 degrees. The retrofitting scheme was successful in increasing strength, however, energy dissipation and re-centering capabilities of SMA bars were not completely utilized mostly due to the length of the bars. Khalil and Ghobarah [10] tested three RC shear walls, which included one control wall and two RC walls strengthened using fiber-reinforced polymer (FRP) sheets to increase shear capacity and ductility of walls. The control wall was deficient in shear and ductility. The strengthened walls were wrapped with bi-directional sheets in the wall region and unidirectional sheets on the boundary regions. The boundary regions had FRP anchors in the upgraded walls. The control wall panel failed before reaching the yield displacement while the two strengthened walls achieved displacement ductility of 3 and 4 before failure started. The strengthened walls sustained on average 50% more lateral load capacity and 60% more lateral drift than the control wall. Other researchers [11,12] also reported the effectiveness of using FRP to improve seismic performance (such as shear capacity, ductility, and energy dissipation capacity) of RC walls. However, it is noted that the anchoring system is the critical part of the FRP strengthening scheme [13].

Although several studies have been conducted on strengthening of RC walls using different materials and techniques, Galal and El-Sokkary [14] pointed out five factors that control the choice of retrofitting techniques for RC walls: (1) the deficiency in the existing wall and its expected failure mode, (2) the goal of retrofit (e.g. increased stiffness, strength, ductility, etc.), (3) consequences of wall rehabilitation (e.g. increased demand on foundation, etc.), (4) the allocated budget for retrofit, (5) physical constraints (e.g. architecture requirements, accessibility of the building during the retrofitting process, etc.). In addition, it is important that the retrofitting construction does not interrupt the occupancy for residential and government office buildings. In this case, retrofitting works may be allowed only on the external side of rooms or buildings to use the internal space during construction.

This paper presents an experimental study on four full-scale lightly RC walls with or without upgrading. The goal of the upgrading was to improve the seismic behavior of lightly RC walls by enhancing both shear and ultimate drift capacities. A prototype wall (NSW2), which was already published in Ref. [15], failed prematurely in shear reproducing the failure mode observed in condominiums in the 2011 off the Pacific coast of Tohoku Earthquake. Two specimens were upgraded by placing additional wall panel and the other specimen was upgraded by improving the reinforcement details. Experimental observations on four walls are reported in terms of lateral load carrying capacity, energy dissipation (ductility), damage process, and failure mode.

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