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Seismic strengthening of low-rise reinforced concrete frame structures with masonry infill walls: Shaking-table test

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ABSTRACT

This study investigates experimentally the seismic behavior of reinforced concrete (RC) frames damaged by earthquakes and retrofitted with masonry infill walls. To this end, a 2/5 scale one-bay one story RC frame structure designed only for gravity loads (without seismic design consideration) was built in laboratory. Initially, it was subjected to several shakings to induce a moderate level of damage characterized by a maximum lateral drift ratio of 1.5% and a residual deformation of 0.12%. Next, the RC frame structure was retrofitted with two masonry infill walls oriented in the direction of motion and subjected to four uniaxial seismic simulations. The structure with infills experienced drift ratios of up to about 5% without signs of catastrophic collapse, and retained a reasonable energy dissipation capacity after the walls reached their maximum strength. The maximum drift reached was surprising given the brittleness of masonry. The results of the test open a realm of the possibilities for infill walls as a seismic retrofit solution. Finally, on the basis of experimental data acquired, a model for estimating the force-displacement relationship of the infills is proposed.

1. Introduction

Reinforced concrete (RC) frames in seismic regions often have unreinforced masonry infill walls. These walls are used as partitions and are considered to be non-structural elements in design. However, in most cases they interact with the bounding frame when the structure is subjected to lateral loads, because isolating the wall from the frame involves cumbersome detailing. Field evidence and numerical simulations have demonstrated that continuous masonry infill walls can help control drift and resist an important fraction of the lateral inertial forces induced by earthquakes. The beneficial contribution of the masonry infill walls can help explain the relatively good seismic performance of old RC frame structures designed for gravity forces only [1]. If their interaction with the frame does not result in column failure, masonry infill walls can help reduce the vulnerability of existing RC frame structures. This study was motivated by the question of whether masonry can be used as a low-cost and low-tech seismic upgrading solution for developing countries located in high seismicity regions such as Dominica, Haiti, and Nepal.

The performance of RC frames with masonry infill walls has been investigated since the late sixties in different ways: analytically with simplified models, experimentally and through detailed finite element analysis methods (for example [2–7]) Past experimental investigations addressed the seismic behavior of masonry infill walls for both in-plane and out-of-plane lateral forces. Most of these studies focused on single-frame single-bay infilled frames under monotonic or cyclic quasi-static loadings. Earlier studies and more recent works (for example [2,3,5,9]) showed that infill walls lead to significant increases in strength and stiffness in relation to bare RC frames, and this has the beneficial effect of reducing the deformations induced by the ground motions (see for example [10–12]) Earlier experimental studies also warned the profession about the reduction of ductility of the infilled RC frame with respect to the bare frame. However, most of these conclusions are based on monotonic static tests and need to be further investigated under earthquake-type dynamic loading. There is a lack of experimental data, particularly from dynamic "shaking-table" tests, to estimate the parameters that control the force-displacement response of the masonry infill walls under lateral loads, or to assess the behavior of the frame-infill system under large lateral displacement demands. The objective of this experimental investigation is to shed light on these issues. More precisely, the main goals of this work are: (i) to provide experimental evidences based on shaking-table tests on the possibilities of masonry infill walls as retrofitting solution for RC frames; and (2) to propose a response model for masonry infill walls. The reliability of the model

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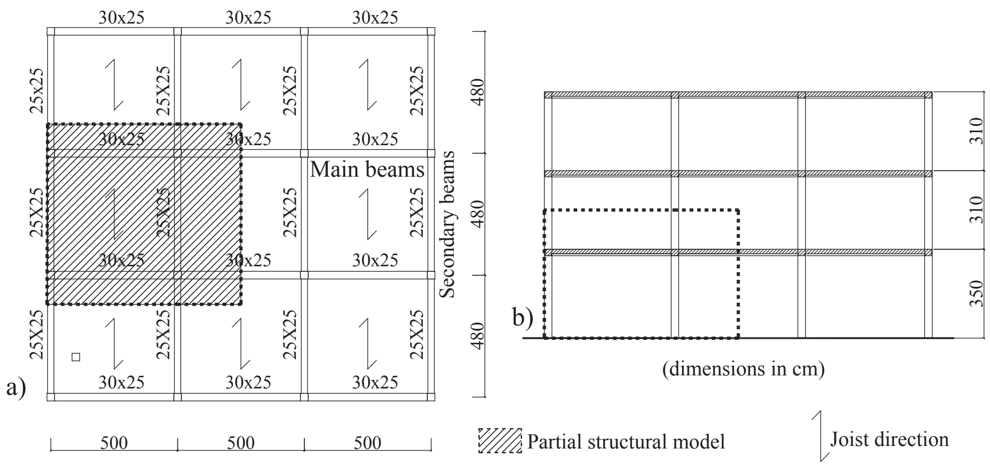

Fig. 1. Prototype structure: (a) plan; (b) elevation. Dimensions in cm.

stems from the type of test (dynamic shaking table tests) used to develop it. Dynamic shaking table tests are the most reliable and realistic way to reproduce seismic demands on structures, including cumulative damage and rate-of-loading effects. This work is part of a more general research project aimed at investigating the feasibility of adding continuous masonry infill walls as a low-cost seismic upgrading solution to reduce the vulnerability of existing RC frames designed only for gravity loads.

2. Experimental program

2.1. Prototype structure and test specimen without infill walls

A three-story 3 × 3 bays prototype structure (shown in Fig. 1) was designed to support exclusively gravity loads applying limit state design method implemented in Spanish codes [13]. This prototype was designed to reproduce the design practices used in European and Mediterranean countries about forty years ago. Because this prototype was meant to represent buildings designed ignoring seismic demands, reinforcement details required for ductile response and “capacity-design” criteria were not used. Superimposed dead loads used in design were 3.2 kN/m^2 (67 psf) for floors, and 3 kN/m^2 (63 psf) for the roof. The live loads assumed were 2 kN/m^2 (40 psf) for floors and 1 kN/m^2 (20 psf) for the roof. A concrete compressive strength of 25 MPa and yield strength of 500 MPa for reinforcing steel were assumed in calculations. The floor system consisted of one-way joists spaced at 80 cm and supported by the frame beams. From the prototype, a partial structural subassembly was extracted by cutting through points of nominal zero bending moment under lateral loads, as shown in Fig. 1. In elevation, this subassembly has the height of the first story and half the height of the second story. In plan it is nearly square, with its length in the direction perpendicular to joist being 1.5 times the beam span in the same direction. A scaled test model of this subassembly was defined using scale factors of $\lambda_L = L_m/L_p = 2/5$ for length, $\lambda_a = a_m/a_p = 1$ for acceleration and $\lambda_\sigma = \sigma_m/\sigma_p = 1$ for stress. Here L refers to length, a to acceleration and σ to stress; the sub index m refers to the test model and the sub index p to the prototype. These scale factors correspond to three dimensionally independent quantities (length, acceleration and stress) whose value can be arbitrarily chosen. The scaling factor for length was set to $\lambda_L = 2/5$ in order to make the dimensions of the test model compatible with the size of the shaking table. The scale factor for acceleration was set to $\lambda_a = 1$ to not distort the gravity force. The scale factor for the stress (and for modulus of elasticity) was set to $\lambda_\sigma = 1$ because it was considered a practical way to conduct true modeling of reinforced concrete structures (the same material is used in model and prototype). Scale factors for the rest of the physical quantities were set to satisfy similitude requirements. Two types of similitude are most commonly considered in structural problems involving scaled models. One is the Cauchy similitude based on the Cauchy number $C_N = \rho v^2/E$. The other type is the Froude similitude based on the Froude number $C_F = v^2/(Lg)$. Here ρ is the specific mass, v the velocity, E the elasticity modulus, L the length and g the gravity acceleration. In these tests the Froude similitude was satisfied, that is, C_F was the same in the prototype and in the test model. An attempt was made to come close to meeting the Cauchy similitude by artificially adding mass to the model. However the Cauchy similitude was not attained due to limitations on the payload capacity of the shaking table. More precisely, the mass artificially added to the test model was about 35% smaller than the value required to make C_N equal in the prototype and in the test model. This means that the mass in the test model represented approximately the mass of two stories in the prototype. Additional mass totaling 91 kN was added to the slab and second-story columns of the test model (Fig. 3). Total weight above first-story mid-height was 120 kN (the centroid of which was approximately 1.75 m above the top of footings).

The geometry and reinforcing details of one of the two identical frames that formed the RC subassembly are shown in Fig. 2a. The frames were connected by the joist floor system and by perpendicular (secondary) beams whose geometry and detailing is shown in Fig. 2b. The yield stresses obtained from tests of bar coupons were 550 MPa for the longitudinal reinforcement and 640 MPa for the stirrups. The concrete compression strength obtained by testing normalized prismatic concrete specimens (150 × 150 × 150 mm^3) was 35 MPa at 28 days and 40 MPa on test day.

2.2. Test specimen with infill walls. Test set-up and instrumentation

The test specimen without infill walls was placed on the uniaxial MTS 3 × 3 m^2 shaking table of the Laboratory of Structures of the University of Granada. Steel blocks (“added weight”) were attached to the top of the slab and to the top of half-height columns in the second story (Fig. 3). To simplify the setup and concentrate deformations in the first story, the upper story of the test specimen was stiffened with diagonal bars thus representing a single story frame whose period is within the range the shaking table can produce the desired demands. Two infill walls (referred to as Wall 1 and Wall 2) were built in the first story in the direction of the seismic motion. The final test set-up is shown in Fig. 3. The infill walls consisted of 2/5 scale masonry units (80 × 40 × 23 mm^3) and joints (4–6 mm thickness) fully grouted with mortar. The mechanical properties of bricks, mortar and masonry are summarized in Table 1. The weight of the test specimen, including added weight, RC frame and one half of the infill walls, was 122 kN.

Longitudinal bars of RC elements were instrumented with strain gauges at member end sections. The locations of the gauges are shown in Fig. 2. Displacement transducers measured the horizontal