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PERFORMANCE OF REINFORCED CONCRETE FRAMES WITH UNREINFORCED MASONRY INFILL DURING THE 2016 ECUADOR EARTHQUAKE

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ABSTRACT

On 16 April 2016, a magnitude (M_w) 7.8 earthquake struck coastal Ecuador and generated over 100 aftershocks ($M_w \geq 6$). The epicenter of the main shock was approximately 29 km south-southeast of Muisne, and had intensities of VIII and IX over a large affected region in the provinces of Esmeraldas and Manabí. More than 10,500 buildings were damaged or collapsed in urban areas, and more 8,100 in rural areas. The affected buildings were primarily concentrated in the municipalities of Bahía de Caráquez, Calceta, Canoa, Chone, Manta, Muisne, Pedernales, and Portoviejo. This paper documents observations made by the author as part of a reconnaissance team that visited the affected sites. Most of the buildings observed were reinforced concrete frames with unreinforced masonry infill and partitions. Extensive non-structural damage was observed in the masonry of both engineered and non-engineered buildings, and structural damage was also common in the RC frames. Observations on the damage patterns are presented, as well as trends associated with the URM panels.

KEYWORDS: *earthquake reconnaissance, infill frames, reinforced concrete, unreinforced masonry*

INTRODUCTION

Over the past four decades, much has been learned about the seismic performance of RC frames with URM infills, and research summaries, analysis and design methodologies and repair and retrofit recommendations have been proposed [1]. Of interest here is an effort to glean any visual observations from the Muisne, Ecuador experience to supplement existing knowledge. Observations are drawn from a five-day reconnaissance of cities in coastal Ecuador affected by the April 2016 earthquake. The qualitative observations of seismic performance are used to 'test' design notions for a structural system that combines non-ductile URM infills with RC frames that are in many cases non-ductile systems.

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2016 MUISNE, ECUADOR EARTHQUAKE

On April 16, 2016, at 23:58 UTC, a 7.8 moment magnitude (M_W) megathrust subduction earthquake occurred where the Nazca plate subducts eastward beneath the South America plate along the Ecuador Trench. Seismic waves struck coastal Ecuador with an EMS-98 intensity of VIII and IX over a large affected region in the provinces of Esmeraldas and Manabí (**Figure 1**). Over 100 aftershocks were recorded within two weeks of the main shock [2], with many of them having moment magnitudes (M_W) exceeding 6.0. The epicenter of the main shock was approximately 29 km south-southeast of Miusne, and its hypocenter was at the depth of approximately 19 km (12 mi) [**3**]. Epicentral distances, in kilometers, to Canoa, Chone, Bahía de Caraquez, Portoviejo, Manta, and Quito, respectively, were 113, 124, 125 and 174.

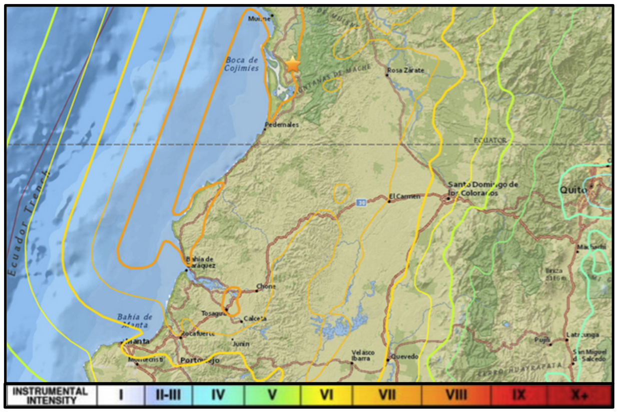

Figure 1: Region affected by earthquake [3]

Peak ground accelerations as large as 1.4g were recorded in the city of Pedernales [3]. High destructive potential have been noted for strong motions recorded in Pedernales, due to high ground accelerations as well as a two-peak response spectrum, and in Chone due to high spectral demand in the 1-2 second period range which was mobilized by the influence of soft soil deposits [4]. Strong shaking and soft soil conditions also created problems associated with liquefaction, settlement and lateral spreading. The final death toll was 668, and more than 16,600 others were injured in the earthquake. A large number of people were displaced, with numbers ranging from more than 26,000 [2] to more than 100,000 [5]. According to the Ministry of Urban Development and Housing of the Manabí Province, over 10,500 buildings were damaged or collapsed in urban areas, and more than 8,100 in rural areas. President Correa of Ecuador has estimated the cost of the earthquake at more than $3 billion [2].

FIELD RECONNAISSANCE

The author surveyed buildings as representative of The Masonry Society (TMS) in a team sponsored by the Earthquake Engineering Research Institute (EERI) and in partnership with Ecuador Army Corps of Engineers (ACE). The EERI team was led by Forrest Lanning (Miyamoto International), and the other members were Ana G. Haro (North Carolina State University), Mei Kuen Liu (Forell-Elsesser Engineers), Alberto Monzón and Héctor Monzón Despang (Guatemalan Association of Structural & Seismic Engineers), Adrian Tola (Virginia Tech University), as well as Lt. Col. Xavier Riofrío (Ecuador ACE). The team's charge was to survey the performance of a representative number of structures in the affected area, including the municipalities of Manta, Portoviejo, Chone, Calceta, Bahía de Caraquez and Canoa [6].

BUILDING STOCK, CONSTRUCTION MATERIALS AND PRACTICES

Coastal Ecuador saw tremendous growth in population and urbanization following WWII, from 1950 to 1980 [**7**]. Most of the building construction in this region comprises a structural form that was very popular throughout South America at that time, and is still popular today, the reinforced concrete (RC) frame with unreinforced masonry (URM) infill. The URM elements are typically clay brick, clay tile or concrete block, and this structural form dominates both engineered and non-engineered construction. Extensive non-structural damage was observed in the URM infills and partitions, and structural damage was also common in the RC frames.

Figure 3: Open head joints

Typical masonry units in Ecuador include 10×30×15cm artisanal clay brick, 20×40cm cement-sand block, and extruded hollow clay tile. These units, in particular the brick, were observed to be relatively soft and weak, exhibiting high porosity along cracked surfaces. These impressions are supported by a survey on the properties of masonry materials in Chimborazo, Ecuador that found that most solid clay brick sampled had unit compressive strengths between 7.3 and 7.9 MPa and most concrete block units between 1.0 and 1.5 MPa [8].

There is concern in coastal Ecuador regarding concrete quality in existing buildings because of past practice of using unwashed beach sand for the concrete mix. While petrographic analysis is needed to ascertain the composition of hardened concrete, a "rule of thumb" is used locally that focuses on the appearance of concrete along cracked surfaces: Sand gradation that appears visually uniform is taken as an indication of beach sand given its narrow particle size distribution. Thus, it is not surprising that many instances of corroded reinforcement in concrete members were observed (Figure 2). Another practice worth noting is the use of smooth bar or wire for transverse reinforcement.

Figure 2: Corroded reinforcing bars

Construction practices were observed that can be detrimental to the performance of RC frames with URM infill. For example, it was noted that head joints in masonry infill and partitions were often left empty or filled only partially (Figure 3). Because the finishing practice is to use thick layers of plaster, as much as 5 or 6mm, the joints would be hidden from view once construction was completed. However, the ability of these URM panels to transfer stresses from lateral loading would be diminished due to the strong discontinuities offered by the open head joints.

PERFORMANCE ISSUES FOR REINFORCED CONCRETE (RC) FRAMES

Reinforced concrete (RC) frame buildings with unreinforced masonry (URM) infill in coastal Ecuador responded to the seismic loading exhibiting many features that have been observed during previous earthquakes in Ecuador and elsewhere. Many of these are typical of non-ductile frames and some of the problems were worsened by idiosyncrasies of the building stock in Ecuador.

Building Configuration Problems

Problems related to soft (low stiffness) and/or weak (low strength) stories were observed, including the formation of story mechanisms and the eventual collapse of these stories. This problem was usually noted in first stories (Figure 4a), but in some cases it was noted for intermediate stories (Figure 4b).

a) First story b) Intermediate story

Figure 4: Story collapses

a) Open first story b) Discontinued RC infill frame

Figure 5: First story discontinuities

Weak stories were usually soft stories, and these resistance inadequacies were often the result of first stories that were taller than the stories above, and first-story floor plans that differed from those in the other stories. First-story floor plans were ‘opened’ by reducing infill lengths to create large window and/or door openings, or by eliminating infills and partitions one or two façades facing the street. These practices result in reduced lateral and torsional stiffness and strength for the first story (Figure 5a). In some buildings, not only were the infills discontinued in the first story, but the columns along the building perimeter as well (Figure 5b). In such cases, the transfer of column axial forces from overturning were also interrupted in the first story.

Short columns failing in shear were observed frequently in damaged or collapsed buildings (Figure 6). These occur typically when masonry infills are discontinued near the top of a story in order to create window openings, and the short length of column that is not supported by the infill is required to resist large shear force reversals. The shear force magnitudes, especially if the column is not well confined with transverse reinforcement, produce large shear cracks and crushing of the concrete core, after which the longitudinal bars buckle. The use of small-diameter column ties placed are at a large spacing further exacerbated the damage to the columns.


Figure 6: Short column

Traditional building architecture in Ecuador utilized colonnades along the street to maximize floor space in stories above the first (Figure 7a). This practice reduces the strength and stiffness of the frames along the colonnade by eliminating the infills along the street façade. However, later architectural developments did away with the colonnade altogether creating large cantilever overhangs along the street, and in the case of corner buildings the overhangs are present along intersecting façades (Figure 7b). The cantilever overhangs worsen the torsional irregularity of first stories, and the infill frames and partitions above the overhangs were identified as a common location of damage requiring shoring following the 2016 earthquake.


a) Traditional colonnade

b) Cantilever overhang

Figure 7: Colonnades and overhangs

Inadequate Member Sizing

In some of the larger buildings surveyed by the EERI team, the use of spandrels led to member sizing in which the beams were stronger than the columns which in some cases led to column hinging and a story mechanism (Figure 4b). In smaller building, especially those with colonnades, some columns were observed to have failed in compression (Figure 8). The combined effects of overturning and vertical acceleration, in combination with gravity loads, exceeded column capacity, and the omission of infill panels eliminated any alternate load paths.

Figure 8: Column compression failure

Inadequate Reinforcement Details

Numerous instances of inadequate reinforcement details for RC frame members were noted. These included excessive tie spacing in columns, which limited the amount of confinement of the column core and restraint against bar buckling (Figure 9a). In other cases excessive stirrup spacing in beams were observed, leading to limited shear strength (Figure 9b). Ties in columns (Figure 10a) and stirrups in beams were often observed to have with 90-degree bends, which increased the likelihood that the ties would open under seismic loading. Transverse reinforcement was also observed to have been made from bars that are too small (Figure 9a). In some cases beam-column joints were noted to have been provided insufficient or no reinforcement (Figure 10b), which resulted in joint failures.

a) Column b) Beam

Figure 9: Inadequate tie spacing

RC Frame URM Infill Interaction

RC frame performance is impacted by the failure of URM infill panels. Besides the hazard posed by falling debris, the failure of URM infill panels can affect frame performance. The concomitant reduction in lateral strength and stiffness of the building will inevitably mobilize increased drift demands, and if the frame has limited drift capacity, as was the case with the buildings described in the preceding, the RC frames may have been unable to attain the augmented drift demands from the ground motion. Damage to the columns, the only remaining elements in the lateral force system, would follow, and partial or total collapse is possible.

PATHOLOGY OF URM INFILL PANEL DAMAGE

Careful consideration must be given to the question of what constitutes an infill panel. An ideal infill panel must be bounded by frame members on all four sides in order to achieve its design intent without premature loss of capacity. The RC frame carries gravity loads and the effects of overturning and vertical accelerations though changes in column axial compression, while the infill panel carries horizontal shear force (V_x in Figure 11). The capacity of the infill panel is drawn from the forces that are transferred from frame to URM panel through shear and bearing stresses along the interfaces. Bearing stresses (σ_x and σ_y in Figure 11) near the frame joints, as well as shear stresses along the length of the interfaces, produce compression struts that transfer loads over the story (Figure 11).

Figure 11: Idealized infill panel response

If the URM infill panel works as intended, it will develop cracks that increase progressively in width (δ_c, δ_x and δ_y in Figure 11) and number as the panel undergoes increasing cyclic drift demands. Depending upon aspect ratio, sliding along the perimeter may initially crack the panel and separate it from RC frame (Figure 12a). If not restrained from out-of-plane motion, transverse loading may initiate out-of-plane displacement relative to the frame (Figure 12a) that can eventually lead to collapse. A well-restrained URM infill will develop inclined cracks if the diagonal tension strength of the URM masonry is exceeded (Figure 12b). Under repeated cycles of load, cracked surfaces will slide generating strength degradation from abrasion and increased crack widths.

a) Cracking around infill panel perimeter

b) Bidirectional diagonal cracking

Figure 12: Infill panel pathology

After many cycles, the cracked panel fragments, and these pieces can collapse out of plane. The transition from ‘expected’ to ‘undesirable’ behavior can be very quick, and infills at this stage can be totally destroyed (Figure 13). Similar observations have been made regarding an RC infill frame specimen tested under simulated earthquake motion in a shake-table [9].

URM INFILL PANEL ISSUES

During the reconnaissance a number of issues were observed that are likely to have affected the performance of the URM infill panels.

Performance of Panel Anchors

In an attempt to restrain URM infill panels from out-of-plane collapse, anchors in the form of reinforcing bars embedded in the bounding columns were observed in some of the surveyed buildings (Figure 13). The anchors were invariably embedded in the horizontal mortar (bed) joints of the masonry, regardless of the type of unit (i.e., solid clay brick, hollow clay tile or hollow concrete block). In many instances the panel anchors were ineffective in preventing out-of-plane collapse of the infill panels (Figure 13). Either the anchor length was insufficient, or the mortar strength was too low, or both.

Figure 13: Panel anchors

Unbounded Infill Panels

The columns bounding a URM infill panel on both sides offer paths for bearing and shear stresses from direct contact, and they provide confinement to the URM panel. If the columns are stiff enough, the confinement keeps diagonal cracks in the URM infill panel from opening as much as they would otherwise open in an unbounded panel. Thus, they enhance the ability of the infill panel to maintain its horizontal shear strength under cyclic loading. If the bounding column on one side of an infill panel, or on both sides, is removed, the ability of the panel to retain lateral strength and stiffness is diminished (Figure 14a). By introducing a door or window opening on one side of a panel bounded by a frame column on another side, the same detrimental effect was observed (Figure 14b).

a) Termination without a frame column

b) Interruption by door opening

Figure 14: Infill walls bounded on one side only

Offset Infill Panels

Infill panels should not be offset from frames for the same reasons offered in the preceding section. If they are, then the necessary contact for shear and bearing stress transfer vanishes, and the panels are reduced to isolated URM elements. In cases for which the frames were offset by large dimensions from the exterior infill panels, collapse of the infill panels was observed (Figure 15a). Even when the offset was only at one end of the infill panel, panel collapse was also noted (Figure 15b). Needless to say, details are needed to prevent out-of-plane collapse of the panels.

a) Offset frame b) Offset column

Figure 15: Offset URM infill panels

Interior Partitions and Exterior Panel Behavior

URM interior partitions behaved in a similar manner as the unbounded infill panels. As far as resistance mechanisms are concerned, these elements are essentially identical. Without restraining details to prevent out-of-plane collapse, interior URM partitions suffered frequent instances of collapse (Figure 16a). Exterior URM panels were often part of a continuous masonry skin that provided restraint to the more heavily stressed regions. Nonetheless, damage to these elements was widespread (Figure 16b).

a) Collapsed interior URM partition b) Damaged exterior URM panels

Figure 16: Interior URM partitions and exterior

IMPLICATIONS FOR REPAIR AND RETROFIT

It is often suggested that damaged RC frames with URM infill panels should be repaired by removing all panels, damaged and undamaged, and replacing them with more flexible systems (e.g. stud walls). However, low-stiffness systems typically have much lower lateral strength than the URM infill panels they replace. This solution would expose the non-ductile RC frames to seismic drifts that could exceed their capacity. Thus, if the infill panels are removed, the RC frame must be retrofitted so that the modified building alone can survive future earthquakes.

Miyamoto has proposed the use of dampers and buckling-restrained braces to retrofit tower buildings [10]. Base isolation technology was shown to be highly effective in protecting the Bahía de Caráquez Bridge during the 2016 Muisne earthquake [6]. However, more cost-effective repair and retrofitting solutions are needed for smaller buildings. A promising technique is the use of engineered cementitious composite (ECC) overlays to repair the URM infills [11]. This measure can provide significant increases in strength and stiffness such that nonlinear displacement demands can be controlled, and it may also enhance ductility.

CONCLUSIONS

Ecuador’s experience during the 2016 Muisne earthquake mirrors that of other earthquake-affected countries that have large inventories of infilled RC frame buildings. Coupling the problems associated with building design and construction, with the intensity of the 2016 earthquake, serves to explain the observed widespread damage. This experience motivates inquiry on the ideal characteristics of RC frame buildings with URM infill panels with the goal of enhancing seismic performance. Moreover, the URM panel is not a robust element: when it reaches its load capacity, failure can be catastrophic. Infill panels in a RC frame perform better if the frame provides confinement that enhances panel characteristics. Specific ‘lessons’ follow.

1) Infill panels that are not bounded on all sides will fail earlier than if they were fully bounded.
2) Under heavy shaking, a fully bounded panel may crack around its perimeter, and out-of-plane loading can collapse the panel unless it is well anchored to the RC frame members.
3) Measures to tie anchor URM infill panels to the frame must be thorough, and reinforcing bar anchors embedded in mortar joints are often inadequate.
4) Interior partitions, offset infill panels and exterior panels behave as isolated elements that rely entirely on effective connection to the RC frame for adequate performance.
5) Removal of damaged infill panels in non-ductile RC frames, and replacement with flexible cladding and partitions is inappropriate unless the RC frame is also retrofitted.
6) A more effective repair/retrofit option is to apply ECC overlays to the URM panels.

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