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THE APRIL 2016 MUISNE (ECUADOR) EARTHQUAKE – BEHAVIOUR OF LOW-RISE RC FRAMES WITH MASONRY INFILL, AND RECOMMENDATIONS FOR NEW CONSTRUCTION

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Abstract: *The 16th April 2016 Mw 7.8 Muisne earthquake in Ecuador caused nearly 700 fatalities, 230,000 injuries and over 35,000 damaged or collapsed homes, leaving 140,000 without adequate housing. The majority of the damaged structures, in particular in urban and peri-urban areas, were constructed from low-rise reinforced concrete frames with unreinforced masonry infill. It was evident by their design that these buildings are generally non-engineered, or at least not correctly engineered, for seismic loads. This paper draws on observations made primarily from the EEFIT reconnaissance mission, augmented from other missions to the affected region, to describe the typical types of damage and failures seen in this building taxonomy, and why these are likely to have occurred. The paper then explores confined masonry as an option for new construction. An example is presented of the successful implementation of confined masonry post-event in the affected region, describing the approach that was adopted, in particular training, promotion and dissemination of the confined masonry technique, as well as the challenges of influencing people's existing perceptions and styles. The paper concludes with a summary of why confined masonry is considered to be a durable, resilient, easy to construct and appropriate form of new construction in Ecuador.*

Introduction

The majority of the building stock in the area affected by the April 2016 Muisne earthquake was low-rise (1-6 storeys) reinforced concrete frame with unreinforced masonry (URM) infill. This system is commonplace for housing throughout the world, because it uses widely available materials, is low-cost and is simple to construct. However, it also has many vulnerabilities, and because of its heavy weight its failure can often lead to injury or death.

This paper seeks to describe the typical types of damage and failures seen specifically in this building stock. It draws on observations made primarily from the EEFIT reconnaissance mission (Franco *et al.*, 2018), but also from other missions to the affected region (Franco *et al.*, 2017; EERI, 2016; GEER, 2016; Kagermanov *et al.*, 2017; Schultz, 2017; Toulkeridis *et al.,* 2017). The paper then explores why confined masonry (CM) is considered to be a more appropriate form of construction moving forward, and an example is presented of the implementation of CM post-event in the affected region.

The April 2016 Muisne (Ecuador) earthquake

A M_w7.8 megathrust earthquake shook Ecuador on the evening of April 16th 2016 at 18:58 local time (23:58 UTC), henceforth referred to as the 'Muisne event' (USGS, 2016). The coastal towns – particularly Pedernales, Canoa, Bahía de Caráquez, Manta and Portoviejo – suffered extensive damage after the mainshock, with associated intensities of VI-VIII on the Modified Mercalli Intensity (MMI) scale. The resulting peak ground accelerations (PGA) recorded at seismometer

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stations by the Instituto Geofísico ranged from 0.51g in Portoviejo to 1.55g in Pedernales (Instituto Geofísico, 2016). Many aftershocks occurred, including several events greater than M_w5, such as the $M_w6.7$ and $M_w6.9$ aftershock events on May 18. Over 350,000 homes were classified as destroyed or damaged, resulting in 140,000 people displaced (Reliefweb, n.d).

Observed Building Stock

There were a number of different building typologies in the earthquake affected region, with varying levels of engineering input, quality, and durability. The main taxonomies observed were:

1. Reinforced concrete (RC) frames with masonry infill walls.
    a. Non-engineered, typically low-rise (<6 storeys).
    b. Engineered, typically high-rise (≥6 storeys).
2. *Quincha/bahareque (bamboo/timber frame with mud render)*.
3. Timber frame with and without masonry infill.

This paper focuses on the behaviour of the non-engineered low-rise RC frames with masonry infill – further information on the performance of the other typologies is available in Franco *et al.* (2018) and van Drunen *et al*. (2016).

Low-rise RC frames with masonry infill walls

This system tended to have a slender RC frame, with thin columns and either a shallow beam or in some cases no beam at all, and a conventional RC slab (flat or ribbed) (Figures 1 and 2). Slender clay brick masonry walls (single skin, sometimes with bricks orientated on their short side, making the aspect ratio of the wall even more slender) formed the façade and internal partition walls of most buildings, which were in some cases connected back to the frame with light reinforcement. These bricks were typically clay bricks, clay tiles or concrete blocks, and weren't particularly strong (Schultz, 2017). Wall density was relatively high, however at ground floor there was often a shop front and/or a sheltered corridor, resulting in lower wall density.

Figures 1 and 2. Typical low-rise RC frame with masonry infill.

These buildings were often built in stages, with the first floor or two constructed first and then additional floors added when money becomes available – they did not generally exceed six storeys in height. The buildings appeared to be largely non-engineered, likely built by a local builder (known as *maestros de obra*) possibly with some input from an architect and limited, if any, input from engineers. In reality, the lateral load-resisting system of these buildings is likely to be the RC frames braced by the masonry infill walls – by inspection the RC frames, without infill walls, are too slender to attract significant load when compared to the stiff masonry wall panel, and it's possible that any hinges may form first in the columns and not the beams. It was also commonly observed for the lowest floor to have more openings (hence these building are very susceptible to soft-storey failures).

The system is not too distant from CM, at least visually, however the construction sequence (frame then masonry instead of vice versa) means the panels are not fully confined and generally not positively connected to the frame. Furthermore, the detailing of the columns and tie beams appeared inadequate, and the masonry wall panels are too slender for out-of-plane loads. As a result, the masonry and the frame do not purposefully act together under lateral load as shear walls, but rather as a frame partially braced by an interfering infill wall. Therefore, these buildings tended to be hybrids, a cross between a moment frame and a CM building, but lacking the correct design and detailing for either.

Observed building damage

This section provides an overview of the different forms of building damage observed following the earthquake. Note that many of the reasons for failure are intrinsically linked.

A) Inadequate design and detailing of RC moment frames

Damaged RC framed structures generally contained some or all of the following issues (Figure 3):

- Inadequate global flexural and shear capacity.
- Strong beam – weak column.
- Lack of capacity design in beams (necessary to ensure a ductile flexural failure mode occurs before a brittle shear failure mode).
- Inadequate detailing for strength and ductility.

Figures 3 and 4. Collapsed building showing failure of frame, and masonry failure out-of-plane.

B) Inadequate masonry infill design and construction

The masonry used to infill RC frames to provide façades and partition walls was inadequate in a number of areas (Figure 4):

- The connections between the columns and the masonry were often insufficient to prevent out-of-plane wall failure. In most buildings no reinforcement bars connected the infill to the frame, or the masonry was offset from the RC frame.
- Where reinforcement bars did exist connecting the columns to the masonry, the masonry was often too thin and the mortar too poor quality to enable the bars to properly bond to the masonry. In addition, the thin mortar meant the bars were not properly protected against corrosion.
- In order to save construction time and material costs, the RC beams and columns were placed far apart, and the walls were single skin and constructed by placing bricks laid on the long narrow side (with the broad face of the brick exposed). This creates a very slender aspect ratio of the panels, which means that the masonry is unable to arch under out-of-plane load, nor able to provide a stable response under in-plane load, and therefore is liable to fail/buckle out-of-plane (Goretti *et al*., 2017).
- Where the designated lateral load-resisting system is a moment frame, the masonry should be de-coupled from the frame through the introduction of a 'soft' joint on three sides of the masonry panel (typically 10-40mm thick), filled with a compressible material. This 'best-practice' was not observed in any building.

Inadequate masonry design and detailing was observed in nearly all buildings that had infill masonry walls.

C) Inadequate shear design and detailing

In seismic areas, the shear links within RC elements need special detailing. In particular, shear links need to be closely spaced, the two ends of the loop need to return into the column by an angle greater than 135 degrees, and the length of the returns need to be sufficient. This detailing ensures that the shear capacity of the concrete is as designed, helps to reduce buckling of the longitudinal bars and helps to confine the concrete in the core. In many RC buildings surveyed, some or all of these detailing requirements were not present (Figure 5 and 6).

Figures 5 and 6. Inadequate design and detailing for shear –link spacing and detailing.

D) Weak and soft storeys

Upper floor soft/weak storey failures occur when a floor is lower in strength or stiffness than the adjacent storeys, resulting in load concentration at this floor level, which can exceed the capacity and result in damage to or collapse of that floor (Figure 7). This form of collapse was seen in a number of buildings, interestingly many of which were at an upper floor instead of a ground floor (which is generally more typical). Some of the soft/weak storey failures were likely due to a discontinuity in frame and/or masonry strength between floors, while it is suspected that others were due to inadequate lapping of primary column reinforcement (see item (E) Inadequate laps).

Figures 7 and 8. Weak/soft storey failure, and exposed reinforcement with possible inadequate lap lengths for future construction.

E) Inadequate laps

A number of buildings experienced upper floor weak/soft storeys without a clear change in stiffness or strength. It is known that the reinforcement bars come in set lengths, and when placed for construction the top of the bars were often observed to rise just above the second floor. It is common to build just two storeys initially and leave extra reinforcement exposed, ready for an additional floor in the future (Figure 8).

In many cases, the amount of reinforcement sticking out waiting for future construction may not be sufficient for a proper reinforcement lap, which would lead to a weak and brittle connection between two distinct phases of construction. In addition, the reinforcement bars are often left out for many years and so can experience surface corrosion, which can weaken their bond to the new concrete once poured. Finally, all of the rebar is often lapped at one height, causing potentially weak spots in the same location in all columns on a given storey. This can cause specific floors to be weaker relative to those above or below.

F) Short columns

This failure occurs when partial height stiff walls are constructed against columns. This construction promotes a brittle shear failure mode prior to a ductile flexural mode (Figure 9). This failure mode was seen in a number of buildings, with a reoccurring detail of elevated windows for the full length of the frame bays.

Figures 9 and 10. Short column failure and insufficient cover to rebar.

G) Insufficient cover to steel reinforcement

Sufficient cover to reinforcement is required to protect the reinforcement against corrosion. In coastal areas, the environment is more aggressive and the requirements for cover increase. In many columns, the cover was very low (0-20mm), which caused corrosion to the steel (Figure 10). For comparison, UK codes generally require around 50mm cover in good quality concrete to provide adequate protection in a coastal environment.

H) Pounding

Pounding occurs when buildings move out of sync in an earthquake and impact on each other. In very few locations seismic gaps were seen in-between buildings and floor slabs were often out of alignment, leading to localised damage due to pounding (Figure 11).

Figures 11 and 12. Pounding of a column head by a slab of an adjacent building, and inadequate design of plastic hinges.

I) Inadequate design of hinges

Designated hinges in RC elements require special detailing to ensure they yield in a controllable and ductile manner, as opposed to a brittle manner. Where hinges were seen, damage was often seen to be brittle, with failure mechanisms involving local concrete crushing and bursting, and buckling of longitudinal reinforcement, instead of pure tensile yielding of bars (Figure 12).

J) Inadequate securing of non-structural elements

Non-structural elements require securing back to the structure in order to minimise injury and damage, to allow occupants to safely escape and in smaller earthquakes to permit continued building functionality after the event. Adequate securing of non-structural elements was rarely seen, with significant damage to facades, furniture, fittings and ceilings (Figure 13).

Figures 13 and 14. Inadequate securing of non-structural elements and poor quality concrete.

K) Poor quality concrete

The concrete used in RC frames was observed to be of low quality in some areas (Figure 14), likely for a number of reasons:

- Inadequate mix design – some concrete clearly had too much or too little coarse aggregate.
- Excess water – with informal construction, it is common to add excess water to the mix to improve workability, which weakens the concrete.
- Poor compaction – some concrete clearly had not been properly compacted and voids were evident at the bottom of pours.

L) Use of sea sand and/or sea water for construction

A number of local engineers and the national media highlighted that some of the damage could be attributed to the use of sea sand and/or sea water for construction. This can lead to salt being incorporated into the concrete, which has two effects:

1. It speeds up the rate of carbonation of the concrete.
2. It speeds up corrosion once carbonation reaches the steel.

Therefore, when combined with poor quality concrete and low cover, salt in concrete can significantly increase the speed of corrosion of the steel. In addition, sea sand and/or sea water can contain other pollutants and organic materials, which could cause other damage to the concrete.

It is worth noting that salt is not proven to directly result in a significant long-term reduction in the strength of the concrete itself, nor is there any further chemical reaction which breaks down the concrete (Neville, 1995).

M) Use of smooth bars as reinforcement

Some of the damaged older buildings contained smooth rather than corrugated reinforcement. Smooth bars are generally only half the tensile strength of modern corrugated high-strength, and their bond is weaker. Therefore, smooth bars will lead to elements with lower capacity and poorer post-yielding behavior due to the lack of good bond between the concrete and reinforcement bars.

Discussion

The seismic performance of low-rise non-engineered RC frames with masonry infill during the Ecuador earthquake is what one would have expected. Damage patterns matched both observations from other earthquakes such as the 2015 Gorkha Nepal earthquake (Dizhur *et al*., 2016) and analysis of similar typical buildings under non-linear numerical analyses (Kagermanov *et al*., 2017). The issue for this typology is considered to be simply that these buildings are neither a moment frame nor a CM building – they lack the correct design and detailing for either system.

The current practice of construction for these systems is not so distant from CM. The CM structural system consists of horizontal and vertical RC *confining* elements built on all four sides of an unreinforced masonry panel (Brzev, 2007). The confining elements work by:

- Enhancing the stability and integrity of masonry walls for in-plane and out-of-plane earthquake loads (confining members can effectively contain damaged masonry walls).
- Enhancing the strength (resistance) of masonry walls under lateral earthquake loads.
- Reducing the brittleness of masonry walls under earthquake loads and hence improving their earthquake performance.

Their overall performance is superior to non-engineered RC frames with masonry infill, and they are a properly codified structural system (Brzev, 2007). They are also very durable and relatively simple to construct. Most importantly, as they do not differ significantly from the current practice of construction, it can be relatively easy to train locals how to build CM themselves because it is not a completely foreign concept.

Reconstruction in CM

Excellent CM guides already exist for low-cost housing in developing countries (Blondet, 2005; SDC, 2007, EERI, 2011). The new Ecuadorian Construction Norm NEC15, introduced in 2016, includes references to CM, however it's concept and fundamental mechanics were neither explained nor understood properly by local builders, engineers and architects. While CM had been used in the past in Ecuador, as it has been in various other Latin-American countries, over the last decades the knowledge and skills required to implement this system have been mostly lost. Locally, the term "confined masonry" is now applied to RC frames with dowels (locally called "chicotes") which are supposed to hold back the infill walls against out-of-plain forces. In most cases these dowel connections failed during the 2016 earthquake (see failure reason (B) above). The earthquake provided an opportunity to re-introduce CM in Ecuador with correct design and detailing practices.

Case study on CM training in Ecuador by SDC[9]

Based on SDC's experiences after the Pakistan earthquake in 2005 and the Haiti earthquake in 2010, their approach to the introduction of CM was twofold:

1. The training of workers and small-scale contractors in the CM technique.
2. The promotion of this building method among the general public, construction professionals and authorities.

This strategy aims to ensure the training of workers in a construction technique that is appealing and familiar to the public, i.e. there is no point in promoting a construction technique and training workers in a system nobody wants to use it.

While in countries such as Mexico engineered CM is used for buildings of up to 5 storeys, the CM technique covered in this project allowed only for the construction of a two-storey house (ground floor and upper floor).

Availability of building materials

In CM, the masonry walls work in shear, therefore their quality and strength is key. Typical locally produced hollow concrete blocks in Ecuador had a strength of 2-4MPa instead of the required 10MPa. Locally produced bricks were slightly better, but still of mediocre quality. Therefore, one of the first steps in the project was to convince the best brick producer in town to increase the quality of his bricks, which was accomplished through a cost premium.

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[9] SDC: Swiss Agency for Development and Cooperation (humanitarian aid branch).

Training of workers

The training of workers included both practical and theoretical components. An initial training of members of the local non-governmental organisation (NGO) ECOSUR and representatives of various government agencies (SECAP[10], SENESCYT[11], Municipality of Pedernales) was done by constructing a small model house over a period of two weeks (Figure 15). Each day would start with a short theory lesson on the building site (Figure 16), followed by a morning's work. Before lunch a longer theory session with PowerPoint presentations was held in a classroom. In the afternoon training was again practical on the building site. This intensive two-week training was extremely short and only possible because of previous knowledge of the technique by an engineer of ECOSUR, and because of the very small size of the house.

Figures 15 and 16. The training house and the delivery of practical construction workshops.

The proper training of masons started in January 2017 in Pedernales, the coastal town at the epicentre of the earthquake. SDC together with Holcim Foundation provided the financing for the construction of 30 houses for families that had lost their homes and who for various reasons could not rely upon official government assistance. ECOSUR trained the workers during the 10 weeks needed to build a house. After completing a first series of houses, the best masons were retained and, under the supervision of a CM-experienced ECOSUR engineer, acted as trainers for the next batch of masons.

Figures 17 and 18. A one and two-storey CM house built by ECOSUR in Pedernales in 2017.

Practical training consisted of 5 days a week working on the construction site, while the theory component was delivered on Saturday mornings in a classroom. The training materials consisted of an illustrated manual (Carlevaro *et al.*, 2018) and PowerPoint slides, developed on a previous project in Haiti. Both were translated to Spanish and adapted to local terms[12], norms and material availability. The effort to develop a local version of SDC's material took a lot more effort and time than initially planned, however without going through this process of adaptation the training would

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[10] SECAP: Servicio Ecuatoriano de Capacitación Profesional (Professional Education Service of Ecuador).

[11] SENESCYT: Secretaría Nacional de Educatión Superior, Ciencia, Tecnología e Innovación (National Secretariat of Higher Education, Science, Technology and Innovation)

[12] Terms can be very different from region to region or country to country. Most textbooks on CM are from Mexico using terms which were not understood in Ecuador.

not have been possible. At a later stage, a 12-part video presenting the construction of a CM house in detail was produced. This again was a major effort, both logistically and financially. The videos, with subtitles in Spanish, English and French, are available on YouTube[13].

Promotion of CM

To be able (and allowed) to promote the CM technique in Ecuador it was essential to obtain official approval by the Ministry of Urban Development and Housing, the National Secretariat for Risk Management, two major universities[14] and the United Nations Development Programme (UNDP). The first dissemination tool developed by SDC was a calendar for 2017 with 20 key messages, targeted at the general public (many of whom were self-builders) (Figure 19). It covered issues including site selection, proper concrete mix methods, design principles and the correct detailing of rebar connections. The calendar was distributed to all municipalities of the earthquake-affected area and to shops of a national hardware distributor.

Figures 19 and 20. Calendar containing key messages for CM construction, and workshop with students building in CM.

Positive dissemination results were achieved through talks at schools, universities and conferences at provincial associations of architects and engineers. Workshops with students were also effective, where small CM structures were built to showcase all of the different connection details required for a house (Figure 20). Significant effort was also made to introduce CM into the teaching curricula of institutions of higher technical education.

Summary

Low-rise non-engineered RC frames with masonry infill performed poorly in the Ecuador 2016, as was expected. The key issue that resulted in poor seismic performance was simply that these buildings are neither a moment frame nor a CM building – they lack the correct design and detailing for either, and, as a result, perform very poorly in earthquakes.

In order for seismically-resistant building techniques to be successful in a post-earthquake reconstruction context, these systems must: (1) be based on familiar concepts, (2) use local materials, (3) be easy to construct and replicate, (4) be affordable, and (5) be functional and desirable to the community. CM is already so close to what people are constructing that it fulfils all of the above criteria nicely. In addition, CM is durable and resilient to earthquakes when properly constructed, and has proved to be a successful construction technique in many other countries. The case study outlined in this paper illustrates that this is also possible in Ecuador and it is recommended that CM be seriously considered as one of the default new construction methods for Ecuador.

Introducing a new construction technique takes time. Changing a habit is changing a culture, and cultural changes require patience. Therefore, any future implementation of CM needs to change the culture of the broader population, influencing not just masons, but engineers, architects and homeowners. This is best accomplished by mixed teams of technical specialists, community organizers and social scientists targeting the population in various different ways. When this is done well, it can have positive and long-term benefits.

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[13] https://www.youtube.com/channel/UCkY3iEnQeNavcQx09rL4z4A/playlists

[14] The Pontifícia Universidad Católica del Ecuador and the Escuela Politécnica Nacional.

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