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PERFORMANCE OF MASONRY BUILDINGS IN THE AUGUST 15, 2007 PERU EARTHQUAKE

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ABSTRACT

On August 15th, 2007, a magnitude 8.0 earthquake occurred in Peru at 6:34 pm local time with epicenter near Chincha Alta. The earthquake was strongly felt in Lima, 150 km to the north. Government estimates indicate that more than 500 people were killed by the earthquake, over 1,000 people were injured, in excess of 40,000 houses were destroyed and 4 hospitals collapsed. With sponsorship from the Council for Masonry Research (CMR), the author represented The Masonry Society (TMS) in a reconnaissance team organized by the Earthquake Engineering Research Institute (EERI). The goal of the investigation was to learn from the field observations made following such disasters, and to disseminate this information so that it can be used to change codes and practices in the U.S. with a view to improving the performance and safety of masonry buildings. Two compelling reasons for TMS to investigate the effects of the August 15, 2007 earthquake in Peru included the large inventory of masonry buildings which have been constructed over the past century, and news reports of widespread damage in the affected region. Structural damage was extensive, especially in adobe and other types of non-engineered construction, while damage to engineered masonry was generally limited in severity and extent. Confined masonry, which comprises masonry walls that are confined by a lightly reinforced concrete frame that is poured after the masonry is erected, performed well, even when it was non-engineered or built with adobe.

KEYWORDS: adobe, confined masonry, damage, earthquake, unreinforced masonry

INTRODUCTION

On Wednesday, August 15, 2007, at 6:41 pm local time, a strong earthquake shook the central coast of Peru [1]. The earthquake was the product of subduction between the Nazca and South American plates, and the resulting rupture is estimated to have had dimensions of 190 km by 95 km [2]. The epicentre was located 50 km west of Chincha Alta, 110 km northwest of Ica, 150 km south-southeast of Lima, and 60 km east of Pisco, and the focal depth was estimated as 39 km [1]. The central coast of Peru is highly active with frequent earthquakes [3]. Large magnitude events were recorded in October 1974 (magnitude 8.1), August 1996 (magnitude 7.7) and August 1942 (magnitude 7.7). The largest event in the region was a magnitude 9 earthquake recorded at a 700-km distance in 1868.

The August 15, 2007 earthquake was intense, with a moment magnitude, $M_w = 8.0$, and the strong motion lasted for an estimated 100 seconds. Such duration of strong motion is twice as long as is typically expected for events of such magnitude [2], and it is expected to have contributed significantly to the extent of damage in the affected region. Ground motion records obtained at various locations indicate frequency contents that vary with site conditions. For stiff, dense gravel deposits, the records indicate significant amplification for a band of periods between 0.04 and 0.3 seconds, while soft soils records indicate periods of importance between 0.2 to 2 seconds [2]. These ranges include expected periods of vibrations for a wide spectrum of masonry buildings.

The August 15, 2007 earthquake produced extensive damage and casualties in a region that includes the cities of Pisco, Chincha Alta and Ica [4]. The United States Geological Survey reported at least 514 deaths, 1090 persons injured, more than 35,500 buildings destroyed, and more than 4,200 buildings damaged [1]. Most of the damage to was observed in non-engineered adobe or unreinforced clay brick buildings. However, instances of damage were also recorded in engineered construction as well.

As part of its Investigating Disasters project, The Masonry Society (TMS), with sponsorship from the Council for Masonry Research (CMR), arranged for the author to join a coalition of teams from the Earthquake Engineering Research Institute (EERI), under the direction of Eduardo A. Fierro (BFP Engineers, Berkeley, CA), the Geotechnical Engineering Earthquake Reconnaissance (GEER), under the direction of Adrian Rodriguez-Marek (Washington State University, Pullman, WA) and the Pontificia Universidad Catolica del Peru (PUCP), which was led by Nicola Tarque (PUCP, Lima, Peru). The objective of the TMS investigation, which was to collect perishable data on the performance of masonry structures from reconnaissance following the extreme loadings of the August 15, 2007 earthquake in the central coast of Peru.

MASONRY BUILDING SYSTEMS AND MATERIALS

Most engineered masonry buildings in central Peru are either reinforced concrete (RC) frames with masonry infills (Fig. 1a), or confined masonry buildings (Fig. 1b). The systems are conceptually similar, but the construction sequence differs. Masonry infills are placed in the RC frames after the concrete has hardened, whereas the masonry panels in confined masonry buildings are erected first, with the concrete members being cast within the finished masonry. Horizontal bed-joint reinforcement is sometimes used in the masonry panels [5]. A hybrid system was also observed in which confined masonry panels were prefabricated and placed in finished RC frames (Fig. 1c)

a) RC Frame with infills b) Confined masonry c) Hybrid system

Figure 1: Engineered Masonry Building Systems

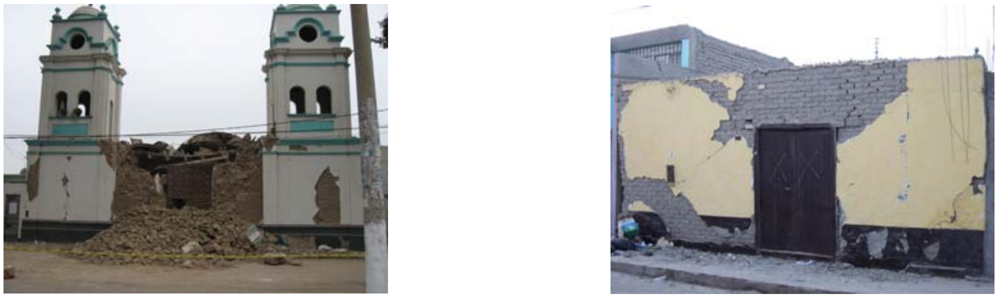
The advantages offered by confined masonry include reduction in formwork, as well as the application of precompression on the unreinforced masonry. The precompression arises from the restraint of the masonry panels on the shrinkage of the concrete members. The associated precompression stress provides several improvements for the unreinforced masonry panel, including enhancement of the masonry shear strength, flexural strength, and integrity. Moreover, since the concrete members are constrained to deform with the masonry, the system behaves as a shear wall with the reinforcement in the concrete members acting as shear wall reinforcement.

Many historic and monumental structures in Peru are built using unreinforced clay brick masonry which is covered in a plaster finish (Fig. 2). The plaster serves as a protective coating for the masonry and mortar, and it allows painted finishes to be applied easily and uniformly. This form of construction is common for churches and older government buildings.

a) Bell Tower b) Commercial Building

Figure 2: Unreinforced Clay Brick Buildings

Lower cost housing, and older monumental structures are typically made using adobe (Fig. 3). Both the adobe units, and the mortar used to lay the adobe units are mixed from local soils. Because adobe is characteristically a weak material, the walls of larger monumental structures often feature multiple wythes. For one-story and two-story residential construction, single-wythe walls are common [6].

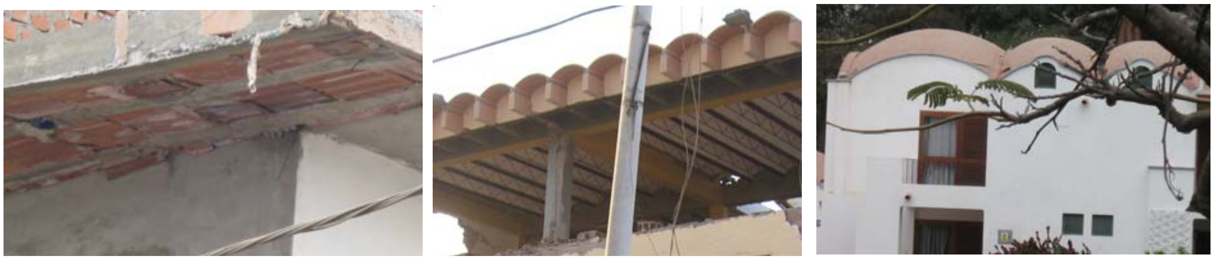


a) Adobe Church b) Adobe Residential Construction

Figure 3: Adobe Construction

Engineered masonry buildings commonly feature RC joist floors, in which clay tile has been used to form the stems of the joists (Fig. 4a). The tile are left in place and given their large void volume they serve to lighten the floor diaphragm. Top stories of engineered buildings sometimes utilize a lighter type of construction that relies on metal bar joists spanning between concrete beams, and clay tile provides an exterior covering with aesthetic appeal (Fig. 4b).

However, the in-plane strength and stiffness of such diaphragms cannot match that of RC joists, especially in the direction normal to the joists. Examples of creativity and ingenuity in the use of masonry can be found throughout Peru, including the use or masonry arches and domes, in contemporary construction (Fig. 4c).



a) RC Joist b) Metal Joist c) Masonry Dome

Figure 4: Engineering Floor/Roof Systems

Roofs in non-engineered construction are typically made using lumber (Fig. 5a) or bamboo joists or rafters (Fig. 5b). Because rainfall is infrequent along the central coast of Peru, sheathing is typically light and comprises either mud or gypsum plaster on crushed cane (known as 'quincha') or woven straw mats (known as 'esteras'). Quincha roofs are used extensively throughout the region, even for vaulted roofs (Fig. 5c). Such roof diaphragms are highly flexible and weak under in-plane forces, and their ability to distribute inertia forces among supported walls during earthquake is limited.

a) Timber Roof b) Bamboo (Quincha) Roof c) Quincha Roof Vault

Figure 5: Non-Engineered Roof Systems

The majority of manufactured masonry units in Peru are either cored clay brick (Fig. 6a) or hollow clay tile (Fig. 6b). The brick are placed such that the cores are oriented vertically, whereas the tiles are placed with the cavities in a horizontal configuration as shown (Fig. 6). Both of these types of units are typically fired in kilns, and they are usually produced with quality control measures to ensure finished dimensions and material properties.

The handmade manufacture of molded units (Fig. 6c) is also common, but the dimensional and material properties of such units are highly variable. For example, clays with high sand contents are often used in the mixture, and the firing process is seldom uniform. As a consequence, these units are often very weak and brittle (i.e., comparable to adobe).

a) Cored Brick b) Clay Tile c) Solid Brick

Figure 6: Clay Masonry Units

Adobe is the most common material for older buildings as well as newer low-cost housing [6]. Adobe units are made by the hand-molding of mud into rectangular units which harden by drying in the sun. Traditionally, these units were made by the homeowner who was building his house, or by a master builder who was hired by the owner. Early units were made using mud with high clay content to provide strength to the finished adobe. In addition, striations were textured onto the top and bottom surfaces of the units (Fig. 7a) so as to provide increased friction with the mud that is used as mortar when laying adobe.

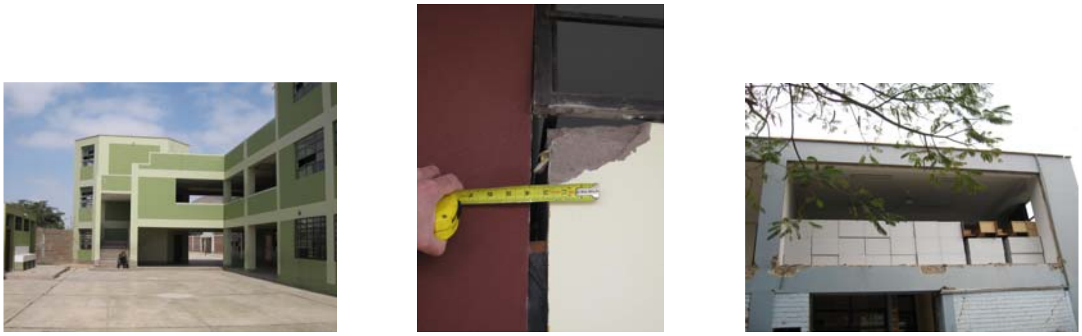
a) Manufactured Adobe b) Smooth Adobe c) Textured Adobe

Figure 7: Adobe Units

Over time the practice of texturing the adobe was dropped in an effort to expedite the production of adobe which was transferred from the homeowner or master builder to a local supplier (Fig. 7b). As the supply of mud with high clay content diminished in a locale, the trend has been to utilize lower quality mud in the production of adobe units. Muds with high sand content and low clay content are often used leading to adobe units that are weaker and softer than older units. More recent trends have led to the commercial manufacture of adobe units that are shaped in molds and which are made using mud mixtures that contain Portland cement (Fig. 7c).

PERFORMANCE OF RC FRAME BUILDINGS WITH MASONRY INFILLS

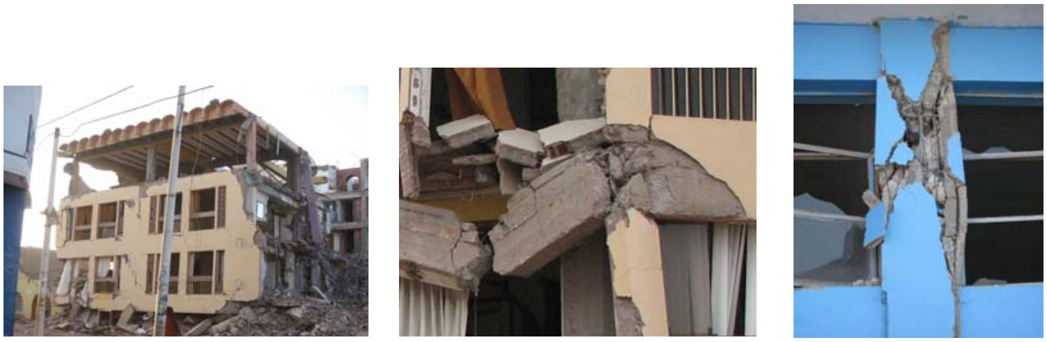
RC frame buildings with masonry infills generally performed well throughout the affect region, particularly those built using the most recent Peruvian seismic design codes and standards. For example, the school building shown in Fig. 8a is located in the town of Guadalupe which is located approximately 10 km north of Ica along the Pan-American Highway. The building shown in Fig. 8a suffered no visible damage during the August 15 earthquake, even though older RC frame buildings in the same school complex displayed minor to moderate damage, and the masonry property wall surrounding the complex included several locations with extensive damage.



a) Undamaged Condition b) Local Crushing c) Infill Out-of-Plane Collapse

Figure 8: Performance of RC Frames with Masonry Infills

One of the concerns with the performance of RC frames with masonry infills has to do with the interaction of these elements along their interface. Fig. 8b shows local crushing damage to a masonry infill in a RC frame building on the campus of San Luis Gonzaga University of Ica. The weather stripping used to seal the isolation gap around the masonry panel fell out during the earthquake, and the metal window frame above the masonry panel has been permanently deformed in a distorted shape. Two problems that are apparent in this detail are that the isolation gap did not include the window frame, and that no measure was taken to prevent out of plane movement of the infill relative to the RC frame. The latter problem was evident among the building stock At San Luis Gonzaga University, and Fig. 8c shows an RC frame for which several masonry infill panels have collapsed out-of-plane due to the lack of connectors to prevent such motion.



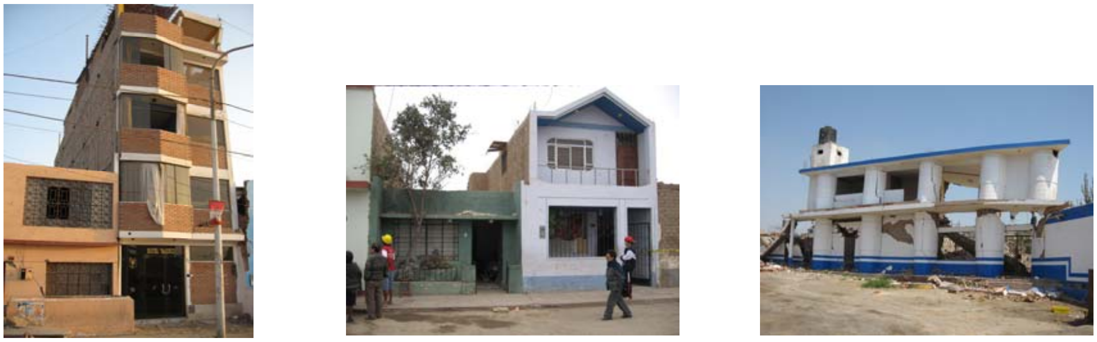
a) Weak First Story b) Inadequate Transverse RF c) Captive Column

Figure 9: Seismic Vulnerabilities in RC Frames

The greatest concern with RC frame buildings, particularly with the older ones, has to do with known vulnerabilities in RC frames that, nonetheless, are left unrepaired or unretrofitted. Figure 9a shows the catastrophic collapse of the Embassy Hotel in Pisco. This building had a weak/soft first story due to the interruption of many of the infill panels in the first story to provide access. A story mechanism comprising the failure of the first-story columns led to instability and collapse of the entire building. Closer inspection of the RC frame members (Fig. 9b) reveals another common vulnerability in existing RC frames with masonry infills in which inadequate transverse reinforcement in the beams, columns and beam-column joints exposes such members to premature shear failure and compression damage. Figure 9c shows a third type of seismic vulnerability that was common throughout the affected region, namely the captive (or ‘short’) column effect. This picture is of a building on the San Luis Gonzaga University in Ica in which the infills are not isolated from the frame thus allowing only the upper portion of the columns to deform laterally. Under earthquake loading, small in-plane deformations of the RC frame impose large shear forces in the 'flexible' portion of the column which to shear cracking. The problem is further compounded by the inadequate design of the transverse reinforcement (insufficient number of ties and excessive tie spacing).

PERFORMANCE OF CONFINED MASONRY BUILDINGS

Confined masonry buildings performed well, even those with multiple stories, as long as the buildings were regular in plan and elevation, and the spans between walls was not excessively large. Figure 10a shows a five-story building that houses the Hotel Madrid in Pisco, only a few blocks from the collapsed Embassy Hotel. The only apparent damage is to the columns in the penthouse level where the masonry was discontinued above the mid-height of the story. In one- and two-story residential construction, confined masonry performed very well in many cases because the wall density (fraction of floor plan area dedicated to structural walls) was high. Figure 10b shows a two-story house in a heavily damaged Guadalupe neighbourhood. No exterior or interior damage was visible in spite of the confined adobe walls used in the first floor. In cases where confined masonry was used in highly irregular buildings, seismic performance was poor. For example, the service station shown in Fig. 10c was located on the Pan-American Highway in the outskirts of Chincha Alta. The triangular floor plan coupled with confined masonry walls along the back of the building and hollow circular masonry columns along the front led to excessive building torsion. The masonry elements were unable to resist the shear forces. The confined masonry wall along the back also indicated extensive weathering damage.

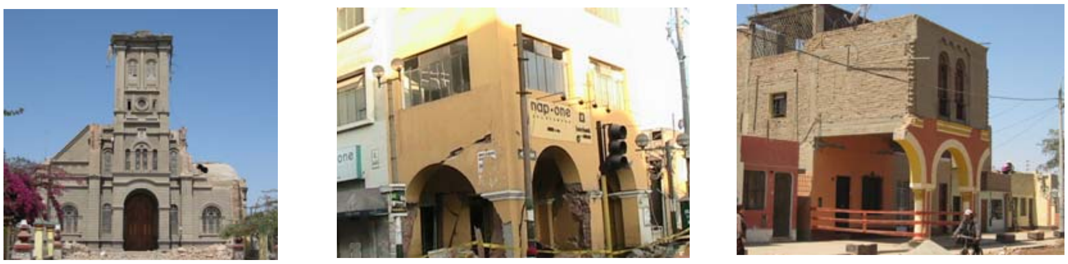


a) Multistory Building b) Residential Building c) Commercial Building

Figure 10: Performance of Confined Masonry Buildings

PERFORMANCE OF UNREINFORCED CLAY BRICK BUILDINGS

Historically, many monumental structures built unreinforced clay brick have performed well by virtue of their massive dimensions. Walls with multiple wythes have maintained stresses sufficiently low to protect the masonry from damage. However, tall bell towers, parapets and large expanses of masonry adjacent to window openings deviate from these ideal conditions. The bell tower and turrets of Our Lord of Luren Church in Ica (Fig. 11a) were slender elements located at the top of the building where seismic accelerations were the largest. As the damaged elements collapsed, they damaged other parts of the church building including the roof diaphragm. Unreinforced brick arches suffered extensive damage in many locations, such as the commercial building in downtown Ica shown in Fig. 11b. Damage typically initiates at the intrados below the crown of the arch and extends upward. The corner pier of this commercial building was also damaged extensively from biaxial nature of the seismic loading at this location. The arch shown in Fig. 11c is a remnant of a series of free-standing unreinforced brick arches surrounding the Luren Plaza in Ica. The only remaining portions of this extensive structure are some spans that were replaced by reinforced concrete arches in an earlier earthquake, and the one shown in Fig. 11c which was on original unreinforced brick span. The masonry building addition supported on the arch served as lateral support, and the precompression from the weight of the addition altered the stress state in the arch allowing it to survive the earthquake.



a) Monumental Structures b) Commercial Buildings c) Masonry Arches

Figure 11: Performance of Unreinforced Brick Masonry Buildings

PERFORMANCE OF ADOBE BUILDINGS

Adobe buildings performed very poorly during the earthquake and suffered the worst damage and largest number of collapses. The adobe and mud mortar are both weak and brittle, thus they fail suddenly without the opportunity for redistribution of forces. The roof diaphragms are weak and flexible, and the connections are not very strong. Thus, only very limited diaphragm action can be expected, often rendering the adobe walls free-standing elements with little resistance to overturning instability.

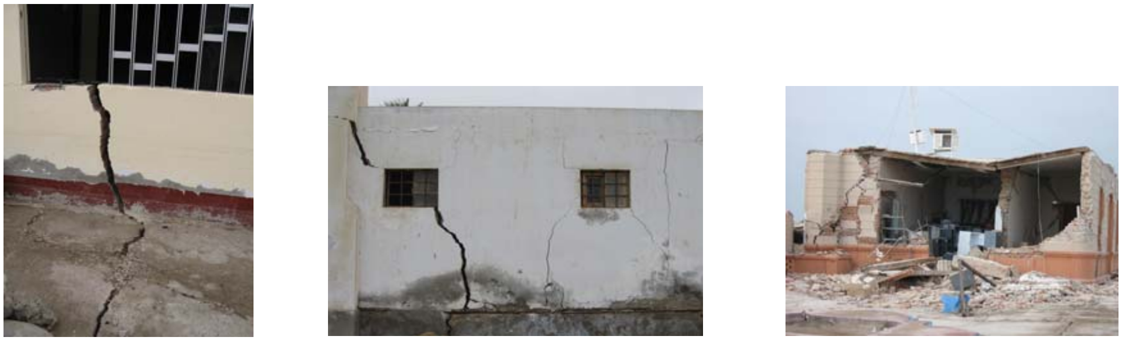
a) In-Plane Damage b) Out-of-Plane Failure c) Wythe Peeling

Figure 12: Performance of Adobe Buildings

The performance of adobe buildings included numerous instances of in-plane shear failure (Fig. 12a). Out-of-plane loading would often force out-of-plane collapses shear-damaged walls. Anther common damage condition was vertical cracking damage at wall intersections. These intersections were typically achieved through bonding of header units, but the stress demands at these intersections often failed the headers. These vertical cracking failures rendered adobe walls unable to resist out-of-plane lateral loading, thus leading to out-of-plane collapses as well (Fig. 12b). In monumental structures, the bond between wythes in multi-wythe walls was often disrupted, leading to the peeling of the outer wythes, and the subsequent collapse of the remaining slender wall.

DAMAGE FROM GEOTECHNICAL EFFECTS

Masonry buildings in certain parts of the affected region were subjected to damaging foundation movements associated with geotechnical effects from the August 15 earthquake. The coastal town of Paracas is located 15 km south of the port of Pisco, and the foundation soils underlying Paracas appears to have spread laterally as a consequence of soil liquefaction in the region [2]. The lateral spreading imposed horizontal deformations throughout most of downtown Paracas, and these deformations manifested as continuous cracks throughout the town with horizontal segments in the pavement and vertical segments in masonry walls (Fig. 13a, 13b). In the port of Pisco, which is located approximately 30 km west of downtown Pisco, numerous locations of ground settlement triggered by soil liquefaction were observed. An unreinforced clay brick masonry building owned by the Pisco Port Authority was heavily damaged as a result of the ground settlement (Fig. 13c.)



a) Lateral Spreading b) Lateral Spreading c) Ground Subsidence

Figure 13: Damage from Geotechnical Effects

CONCLUSIONS

Based on the reconnaissance of the central Peru coastal region affected by the August 15, 2007 earthquake, the following observations and conclusions regarding the performance of masonry buildings are offered.

- The ground motions in the affected region were intense, had long durations of strong motion, and contained spectral acceleration amplification in the range of periods which includes most masonry buildings.
- The affected area was large and encompassed three Peruvian coastal cities in the region of greatest damage.
- Adobe buildings suffered the worst damage and the largest number of collapses. Certain characteristics of traditional adobe construction make it ill-suite for resisting earthquakes.
- Many unreinforced brick masonry buildings were heavily damaged. For monumental structures, the damage appears to have initiated at tall and/or slender appendages.

- Confined masonry buildings performed well by comparison, especially for structures with regular floor plans and elevations, and short spans between walls.
- RC frames with masonry infills performed very well if they were designed according to the most recent Peruvian codes and standards. However, existing RC frames have numerous seismic vulnerabilities which can make them hazardous during earthquakes.

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