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STRUCTURAL DAMAGE IN HOUSING AND APARTMENT BUILDINGS DURING THE SEPTEMBER 7, 2017 TEHUANTEPEC EARTHQUAKE

E. Godínez-Domínguez[(1)], A. Tena-Colunga[(2)], H. Archundia-Aranda [(2)], A. Gómez-Bernal [(2)], R. Ruíz-Torres [(1)], J. Escamilla-Cruz [(3)]

[(1)] *Professor, Facultad de Ingeniería, Universidad Autónoma de Chiapas, Campus-I, Blvd. Belisario Domínguez, km 1081, S/N, Col. Terán, 29050, Tuxtla Gutiérrez, Chiapas, Mexico.* eber.godinez@unach.mx, raul.ruiz@unach.mx
[(2)] *Professor, Universidad Autónoma Metropolitana, Departamento de Materiales, Av. San Pablo 180, Col. Reynosa Tamaulipas, 02200, Ciudad de México, Mexico;* atc@correo.azc.uam.mx, archundia@correo.azc.uam.mx, agb@correo.azc.uam.mx
[(1)] *General Manager, Ingenyos, Paraíso, Tabasco, México.* josescamc75@hotmail.com

Abstract

Mexico is located among five tectonic plates which generate earthquake in most of its territory; therefore, it is one of the most seismically active countries in the world. Historically, strong earthquakes have affected not only nearby epicentral areas, but also large urban areas located at relatively large distances from seismic sources. Given the high seismic risk and hazard of Mexico, a high vulnerability of masonry housing in Mexico has been frequently observed during strong earthquakes. The origin, causes, and effects of the typical observed damage patterns during the September 7, 2017 Tehuantepec earthquake (M_w=8.2), in masonry houses and apartment buildings, located in cities and towns of the Mexican states of Chiapas and Oaxaca in a radius of about 250 km from the epicenter are reported and discussed in this paper. The high structural vulnerability and the severity of the earthquake resulted in the death of 96 people and more than 110,000 houses damaged, where more than 41,000 were considered total losses.

Keywords: Seismic damages; masonry; housing; Tehuantepec earthquake; structural irregularity.

1. Introduction

Mexico is located among five tectonic plates which generate earthquake in most of its territory; therefore, it is one of the most seismically active countries in the world. Historically, strong earthquakes have affected not only nearby epicentral areas, but also urban areas located at relatively large distances from seismic sources. For example, past strong earthquakes generated on the Pacific coast of Guerrero and Michoacán states, such as the March 14, 1979 Petatlán Earthquake and the September 19, 1985 Michoacán earthquake, the central region of the country, located more than 300 km away, has been affected, particularly Mexico City. Chiapas and Oaxaca are two of the states located at the southeast of Mexico with the greatest seismic risk and hazard. The seismicity of this region is generated by the interaction of three tectonic plates: the Cocos plate, the North American plate, and the Caribbean plate (Fig. 1). The seismic hazard of Chiapas and Oaxaca states is clearly specified in the seismic regionalization originally proposed by Esteva [1] and which it has been available during decades in the Manual of Civil Structures (MOC), one of the model design codes in Mexico, with its respective updates [2, 3]. From 1900 to August 2017, Mexico has experienced four very strong earthquakes with magnitude equal to or greater than 8.0 (Fig. 1). However, according to information from the Mexican Seismological Service [4], on September 7, 2017, at 23:49:17 hours (04:49 UTM), an earthquake of magnitude 8.2, located in the Gulf of Tehuantepec, 133 km southwest of Pijijiapan, Chiapas, occurred. The earthquake's epicenter was located at 14.761º N, -94.103º W, with a focal depth of 45.9 km (indicated by the red blast mark in Fig. 1). This earthquake was felt in the south and center regions of Mexico, being affected primarily the states of Chiapas, Oaxaca and Tabasco, and it was felt strongly in Mexico City, about 741 kilometers away from the epicenter (Fig. 1). It is worth noting that there was no damage reported in Mexico City.

Typical observed damage patterns during the September 7, 2017 Tehuantepec earthquake (M_w=8.2) in masonry houses and apartment buildings located in Chiapas and Oaxaca states of Mexico are presented in this paper.

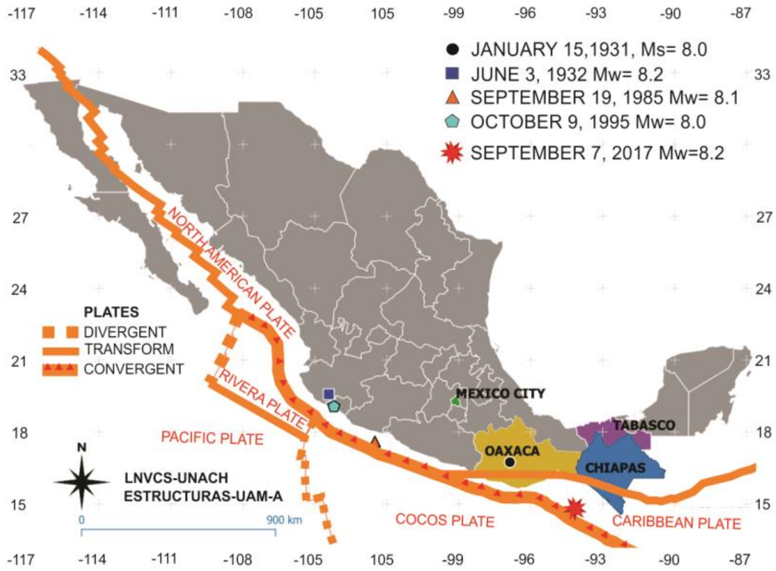
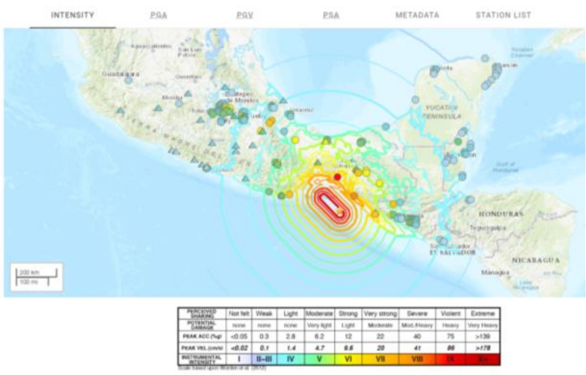


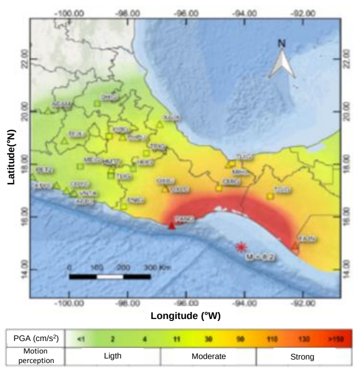
Fig. 1 – States of Mexico with greater affectations during the Tehuantepec earthquake (M_w=8.2)

1. Main characteristics of the earthquake

As commented above, the September 7, 2017, M_w=8.2 Tehuantepec earthquake, occurred at 23:49:17 hours (04:49 UTM), and it was located in the Gulf of Tehuantepec, 133 km southwest of Pijijiapan, Chiapas, Mexico [4]. The earthquake was felt in the south and center region of the country (Chiapas, Oaxaca, Tabasco and Mexico City, Fig. 1). According to SSN [4], the earthquake's epicenter was located at 14.761º N, -94.103º W, with a focal depth of 45.9 km. As it can be seen from the seismic intensity maps shown in Fig. 2, the maximum intensities were found in the Gulf of Tehuantepec area, so the coastal cities in that region were the most affected by the earthquake. A normal fault type (strike=311º, dip=84.4º, slip=-94.7º), which is characteristic of an intraplate earthquake, was determined according to the focal earthquake mechanism. In this region, the Cocos plate is subducted beneath the North American and Caribbean plates [4].



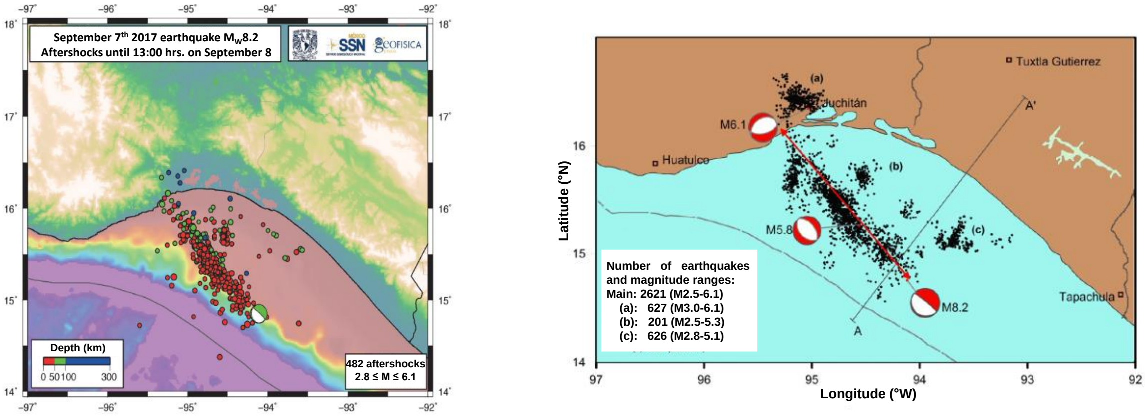
a) Intensity map reported by USGS (https://earthquake.usgs.gov/earthquakes/eventpage/us2000ahv0/map)



b) PGA map [5]

Fig. 2 – Epicenter location and intensity maps of the September 7, 2017 earthquake

According to SSN [4], 482 aftershocks were registered two days after the earthquake (Fig. 3a), and 4,326 aftershocks 15 days later, distributed throughout the Gulf of Tehuantepec (this includes all the seismicity detected in the region). A total of 4737 aftershocks were registered. Two major aftershocks are shown in Fig. 3b. The first one, with a magnitude 5.8, occurred on September 8 at 00:24 hours and it was located 72 km southeast of Salina Cruz. The magnitude of the second aftershock was 6.1, and occurred on September 23 at 07:52, near of Unión Hidalgo, Oaxaca. The red line indicates the length of the fault corresponding to the main earthquake (approximately 230 km).



a) Until 13:00 hrs. on September 8th, 2017 b) Until November 2017

Fig. 3 – Reported aftershocks (adapted from SSN [4])

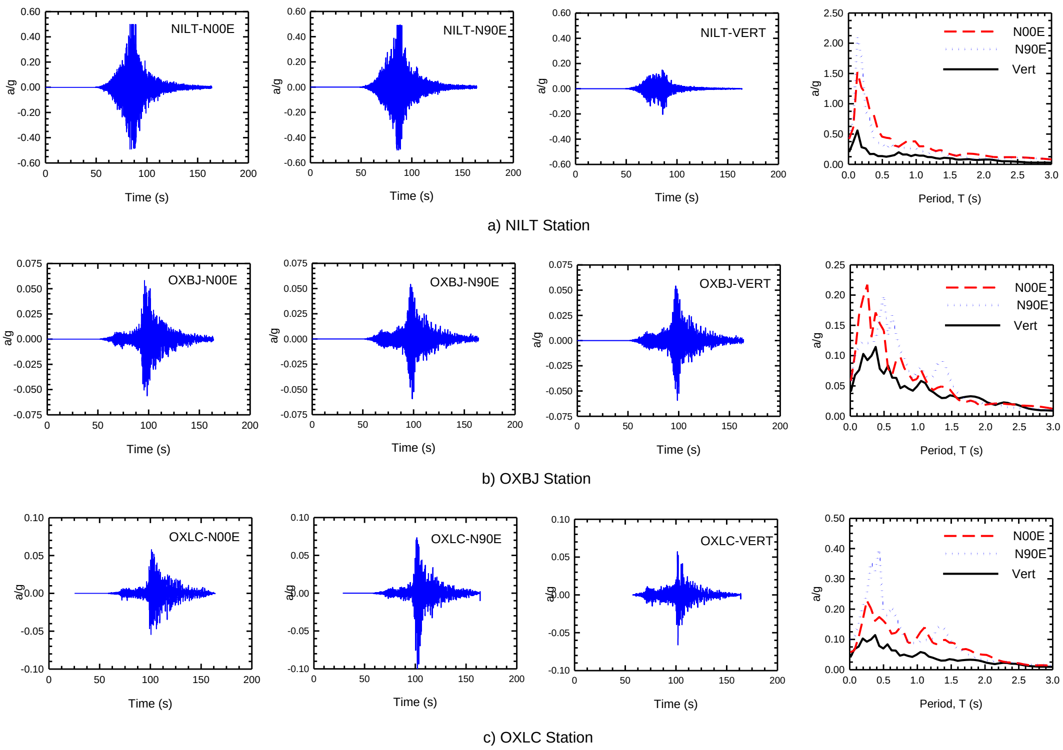


Fig. 4 – Ground motion records and corresponding pseudo acceleration spectra. Information from accelerometric stations operated and maintained by the Seismic Instrumentation Group of Instituto de Ingeniería, UNAM

The three components of some ground motion records, as well as their corresponding pseudo acceleration spectra for 5% equivalent viscous damping are depicted in Fig. 4. The ground motion records shown in Fig. 4 are the product of the instrumentation and processing work of the Seismic Instrumentation Group of Instituto de Ingeniería, UNAM. It is worth noting that, in order to better appreciate the graphs, independent scales are considered for the plots of each station, as depicted in Fig. 4. The maximum acceleration, approximately 500 cm/s^2 (0.51g) was recorded 197 km from the epicenter, at Niltepec station (NILT, Fig. 4a), located in rock. It is clearly observed that peak spectral accelerations are associated to high frequencies (low periods of vibration). For example, for Niltepec station, peak spectral values (which are quite high) are related to those periods below 0.2 seconds, then low-rise rigid structures were subjected to high acceleration demands in this zone.

As a consequence of the earthquake, landslides were observed in several places, particularly on roads which communicate the visited cities (Fig. 5).

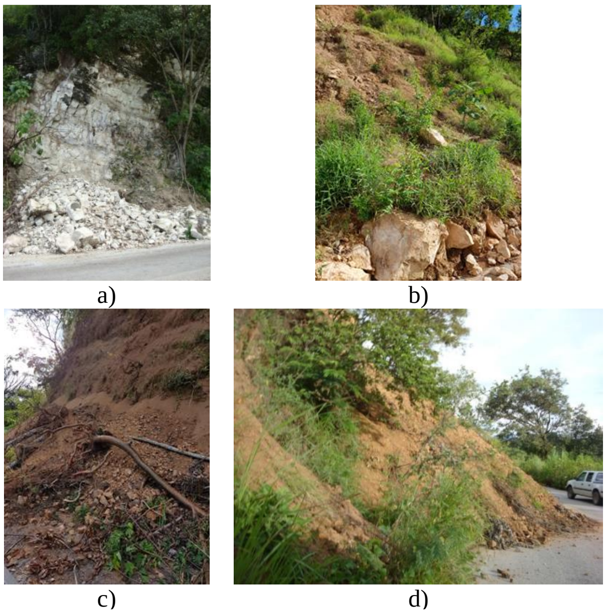


Fig. 5 – Some landslides observed on roads connecting Tuxtla Gutiérrez and Guadalupe Victoria (a) and Villaflores and Tonalá (b, c, d), Chiapas

2. Damage in masonry structures for housing

Most of the housing inventory in Mexico, both in the cities and in the countryside, is built using masonry-based structural systems in their different modalities: unreinforced masonry (URM), confined masonry (CM) or lightly internally reinforced masonry (LRM). Although confined masonry is the dominant mode of construction for housing in Mexico [6, 7], there is an important inventory of houses in which URM and internally reinforced concrete block masonry walls are used.

According to the Ministry of Agrarian, Territorial and Urban Development, 65,044 homes were damaged in Oaxaca, of which 26,949 (41%) were considered total losses. Also, 46,773 homes were damaged in Chiapas, of which 14,073 (30%) were considered total losses. More than 65,000 people were affected. Therefore, representative damage patterns observed in masonry houses and apartment buildings located in Chiapas and Oaxaca states of Mexico (Fig. 6) are presented and discussed in this section.

The visited places were: San Cristóbal de las Casas, Tuxtla Gutiérrez, Berriozábal, Cintalapa, Pijijiapan, Tapachula, Jesús María Garza, Villaflores and Tonalá in Chiapas; Santo Domingo Tehuantepec, Salina Cruz, Matías Romero and Juchitán de Zaragoza in Oaxaca, as well as intermediate points between these cities (Fig. 6). The circles depicted in Fig. 6 were plotted as a reference, and have a radius, measured from the epicenter, ranging from 50 km to 350 km, with constant increments of 50 km each.

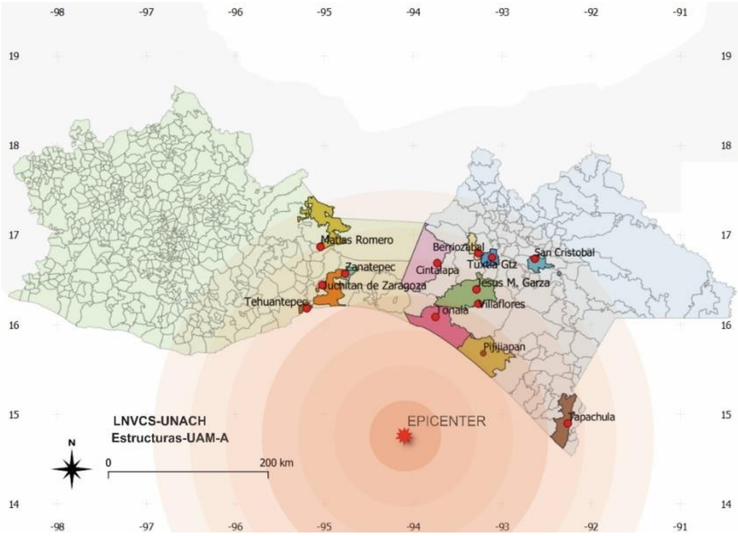


Fig. 6 – Geographical distribution of the visited places

2.1 Confined masonry wall houses

Confined masonry is widely used in Mexico [6, 7]. However, it is common in non-engineered construction that provided confinement elements are deficiently disposed or they are insufficient. In non-engineered constructions, the following components are often not well confined: a) door and/or window openings, b) slender walls (wallets), frequently used in kitchens and bedrooms and, c) parapets. Sometimes, the separation between tie-columns is greater than the maximum recommended in design codes. In some instances, bond-beams are simply not used. Unfortunately, some of this confinement construction deficiencies are sometimes also observed in housing projects assisted by architects or engineers, as it is discussed later. A particularly interesting case was observed in Pijijiapan, Chiapas, where the out-of-plane failure of confined masonry walls was registered as a consequence of the lack of lateral support, given that the house had a light wooden roof simply supported on the walls (Fig. 7). There was also a lack of confinement in the window opening, which it is unfortunately typical in self-construction.

Fig. 7 – Out-of-plane overturning because of inadequate confinement of walls and as a consequence of the lack of lateral support, Pijijiapán, Chiapas

The observed typical damage on several poorly-confined masonry houses located in Juchitán de Zaragoza, Oaxaca is depicted in Fig. 8. It is shown the common diagonal tension failures in walls (Figs. 8a-d), whose cross shape is due to the reversible nature of the earthquake. Despite of having confining tie-columns, their placement is deficient, as confining tie-columns are absent within window openings. In addition, their detailing, construction materials and/or construction process was deficient. Commonly observed errors were: a) inadequate spacing of transverse steel reinforcement (stirrups) and, b) 90 degree hooks in stirrups (reducing the effectiveness of confining the concrete core and supporting the longitudinal bars). In the house shown in Fig. 8b, there was also an evident lack of bond between the concrete slab at the ground floor and the low bond-beam for the walls on the second floor, as well as an inadequate connection between the tie-columns and the concrete slabs (which it is direct, as bond-beams do not exist). A particularly interesting case is shown in Fig. 8d, where in addition to the diagonal tension failure of the wall between windows on the second floor, two walls on the ground floor almost completely overturned out of their plane. This was a consequence of having been built as a RC frame with masonry infills, and not having effectively restricted their potential out-of-plane overturning, connecting them by means of steel angles to the floor system, as recommended, for example, in Mexican masonry guidelines [8].


a)

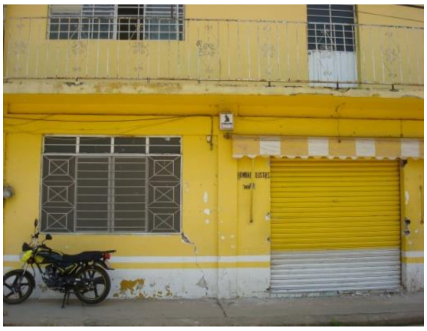

b)


c)


d)

Fig. 8 – Observed damage in poorly confined masonry houses, caused by different design/construction errors in Juchitán, Oaxaca

Diagonal tension damages in walls due to deficient confinements also occurred in other cities where the seismic accelerations were notably lower than in Juchitán, for example, in Matías Romero, Oaxaca (Fig. 9). A diagonal tension cracking near a large, unconfined window opening is shown in Fig. 9a. The most interesting case is shown in Fig. 9b, where it can be observed that the diagonal tension cracking on the ground floor is a consequence of the absence of a tie-column that confines the door opening, because paradoxically, in that region, a tie-column exists in the door of the upper level, where there was no damage.


a)


b)

Fig. 9 – Observed damage in poorly confined masonry houses, in Matías Romero, Oaxaca

The observed damage in different houses located in the cities of Tuxtla Gutiérrez and Berriozábal, both in the state of Chiapas, are shown in Figs. 10 and 11. In this case, according to the owner, the house shown in Fig. 10 had an architectural design, but not an engineering design. The three-story house developed significant damage in practically all walls on the second story, associated with an inadequate confinement of the masonry, since the door and window openings were not delimited by tie-columns and bond-beams (Fig. 10b). A lack of confinement elements was observed, not only in door and window openings, but also in long walls, exceeding the recommendations of Mexican masonry guidelines for these cases. This defect is common in self-construction housing, even in middle and upper-middle class housing (even in cases where architects are involved), as it has been observed in other earthquakes in Mexico [9-11].

a) Rear facade b) Unconfined window opening

Fig. 10 – Damage due to inadequate confinement in a house located in the Terán neighborhood of Tuxtla Gutiérrez, Chiapas

Serious structural diagonal tension damages to the facade walls of the ground floor were observed in the house shown in Fig. 11. This was again due to the inadequate/lack of confinement of the openings, as well as the inadequate detailing of the short elements located on the second floor (which forms the openings for illumination of the stairwell, Fig. 11a). As observed in Fig. 11b, it is clear that due to the practice of placing sanitary piping inside structural confinement elements (tie-columns), their resisting area is significantly reduced, leading to a poor masonry performance. It should also be noted that, in addition, masonry is usually built using non-industrial hollow concrete blocks, with no quality control [12].

a) b)

Fig. 11 – Damage to houses located in the city of Berriozábal, Chiapas

The high seismic vulnerability of houses using poorly detailed or designed earthquake-resistant structural systems was once again evident, as observed from the pictures shown in Figs. 7 to 11. In general, the use of self-construction processes, without adequate technical advice, leads to seismically vulnerable homes.

Houses built using self-construction processes are generally more vulnerable than those in which planning, integrated design (architectural, structural, facilities) and technical supervision are carried out. This is true provided that the proper application of all these items is warranted. However, when the structural design and/or the engineered supervision are deficient, serious damages can also occur to structures in which architects and/or engineers have participated.

A clear example of the latter is shown in Fig. 12, which corresponds to the observed damage in a residential house located in Tuxtla Gutiérrez, Chiapas (Fig. 6). In this case, in theory, both a “formal” structural design and specialized technical supervision was carried out. The severe structural damage observed (total loss) was a clear indicator of the poor quality of the construction materials used (concrete, mortars, non-industrial clay bricks, etc), the poor quality of the workmanship and an inadequate architectural and structural design. The following shortcomings can be observed, among others: a) low wall density area to carry shear forces in the direction parallel to the facade, b) diagonal tension failures in walls, c) shear failures in confining RC tie-columns, (d) shear failures due to sliding along bed joints (Fig. 12d), e) buckling and fracture of the steel reinforcement of the confining elements (Fig. 12b), f) inadequate connection (lack of bond) between the ground-floor slab and the second-floor masonry walls (Fig. 12a). Clearly, in this case, in addition to what it was previously mentioned, there was negligence on the part of those in charge of the execution, supervision and revision of the construction.

Fig. 12 – Severe structural damage to a residential house located in Tuxtla Gutiérrez, Chiapas (photographs courtesy of BSc. Christian Burguete D'Artote)

2.2 Housing buildings with masonry walls

Inadequate structural behavior due to poor confinement did not only occur exclusively in houses, but also in apartment buildings.

A four-story apartment building in which all the windows of the facade wall are not adequately confined is shown in Fig. 13. As it can be observed, the parapet collapsed as a consequence to the inadequate design and/or construction process, affecting the neighboring low-rise building to the left. The building also had a structural system prone to develop a soft-story mechanism, which fortunately it did not develop.

a) b)

Fig. 13 – Observed damage in an apartment building due to inadequate confinement, located in the Terán neighborhood of Tuxtla Gutiérrez, Chiapas

Two four-story apartment buildings located in Juchitán, Oaxaca are shown in Fig. 14. The masonry walls failure due to the lack of adequate confinement is evident in the building shown in Fig. 14a, and it may have triggered by the following reasons. It can be seen that, as usually done for commercial purposes, large open spaces without walls are frequently used on the ground floor, so the building configuration has the potential to develop a soft and weak story. However, this soft-story did not develop because the building previously experienced structural pounding with the house on its right at the second level, and this impact, which fortunately occurred directly between the floor systems of both buildings, led to unconfined wall shear failure on the second story and the severe cracking on the third story.

The building shown in Fig. 14b developed lighter diagonal tension damage in the facade wall on the second and third levels and in the wall between third level windows. Both damages were caused by the structural pounding with the two-story self-construction house to its right, which it seems to be part of the same property.

a) b)

Fig. 14 – Damage to masonry walls of apartment buildings located in Juchitán, Oaxaca

The damage observed in a four-story confined masonry building located in Tonalá, Chiapas is shown in Fig. 15. It is clear that the building has been built in different stages, where the first two stories are the original ones, and the last two stories have been added recently. In addition, the absence of RC tie-columns in window openings is evident. Curiously, there is an intermediate RC bond-beam at the top of window openings. A constructive or modification error was also observed, where the window openings to the right of the photographs were reduced in size using clay bricks in a later construction stage, so that there is a vertical joint in the absence of continuity in the construction process (Fig. 15b).

It is also worth noting that many of the observed damages were magnified by undesirable structural irregularity conditions, primarily the following ones: diaphragm flexibility, soft and/or weak stories and torsion in corner structures, as well as structures that simultaneously had several structural irregularity conditions. Many of the observed damage were also magnified or have its origin in the structural pounding between adjacent structures.

a) b)

Fig. 15 – Damage to masonry walls in a four-story apartment building in Tonalá, Chiapas

2.3 Site effects

Most of the observed damage in Juchitán, Oaxaca, in addition to the structuring and/or construction problems mentioned above, may have also been related to weak soil conditions in which these structures were located. As shown in Fig. 16, a large region of the inventory of severely damaged structures in Juchitán was found in the areas nearby the banks of Los Perros River. Given that the riverbed may have changed over the years, as well as the fact that the soils on its banks are of poor quality due to water filtrations along the sides of the riverbed, soils of poor quality are obtained in its vicinity, and therefore, unfavorable site effects are observed. The red circles shown in Fig. 16 represent not only a damaged structure, but in some cases, they refer to the location of several damaged constructions, as often several damaged structures were contiguous and numerous.

It is worth noting that site effects due to the proximity to riverbanks were not only observed in Juchitán. For example, in Tehuantepec, Oaxaca, severe structural damage was also concentrated in the area located close to the river, in the center of the city, but mainly affected colonial palaces and churches, which are not the focus of this paper. Surely, in many other sites of the states of Chiapas and Oaxaca, it will be possible to document site effects by soft soils close to riverbanks, lakes, lagoons, and beaches, or poorly built filling soils over water surfaces (rivers, lakes, lagoons, estuaries, sea, etc.).

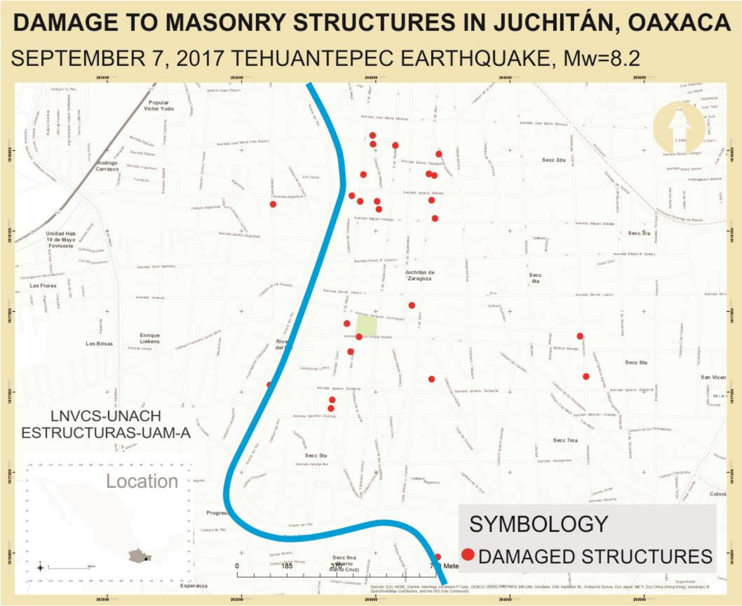


Fig. 16 – Geographical location of severe damage to housing and apartment buildings in Juchitán, Oaxaca

3. Concluding remarks

Typical observed damage patterns during the September 7, 2017 Tehuantepec earthquake (M_w=8.2) in masonry houses and apartment buildings located in the southeast of Mexico (Chiapas and Oaxaca states) were presented in this paper. According to the observed damage, the following conclusions can be done.

Most of the observed damage is repetitive and it is mostly due to poor design, inadequate construction processes, poor quality of construction materials, and lack of specialized supervision or inadequate traditional construction techniques. Many of the observed damages were magnified by undesirable structural irregularity conditions, primarily the following ones: diaphragm flexibility, soft and/or weak stories and torsion in corner structures, as well as structures that simultaneously had several structural irregularity conditions. Many of the observed damage were also magnified or have its origin in the structural pounding between adjacent structures.

The high structural vulnerability and the severity of the September 7, Tehuantepec earthquake resulted in the death of 96 people, most of them (76 people) in Juchitán, Oaxaca. In Oaxaca, 41 municipalities were affected, including: Juchitán, Matías Romero, Unión Hidalgo, San Dionisio del Mar, and the state of Chiapas, Tonalá, San Cristóbal de las Casas, Pijijiapan, Cintalapa, Tuxtla Gutiérrez, Berriozábal, Tapachula, as well as small communities. There was also damage in Villahermosa, Tabasco. According to the Mexican Ministry of Agrarian, Territorial and Urban Development (SEDATU), 65,044 homes were damaged in Oaxaca, of which 26,949 (41%) were considered total losses. Also, in Chiapas, 46,773 homes were damaged, of which 14,073 (30%) were considered total losses. More than 65,000 people were affected.

The extent of the damage caused by the September 7, 2017 Tehuantepec earthquake (M_w=8.2) was much greater than what it is shown in this paper, which focuses exclusively on the damage to housing and just for the cities and communities that were visited. For example, in the cities of San Cristóbal de las Casas in Chiapas and in Juchitán, Tehuantepec and Matías Romero in Oaxaca, damages of great magnitude were observed in diverse churches, government palaces and other historical structures, representing very significant economic and cultural losses.

4. References

[1] Esteva L (1970): Regionalización sísmica de México para fines de ingeniería. *Ingeniería Sísmica*, **2**, 1-33 (in Spanish).

[2] Tena-Colunga A, Mena-Hernández U, Pérez-Rocha LE, Avilés J, Ordaz M, Vilar JI (2009): Updated seismic design guidelines for buildings of a model code of Mexico. *Earthquake Spectra*, **25** (4), 869-898, http://dx.doi.org/10.1193/1.3240413.

[3] MOC-15 (2015): *Manual de diseño de obras civiles*. Diseño por sismo. Comisión Federal de Electricidad (in Spanish).

[4] SSN (2017): *Reporte especial*. Sismo de Tehuantepec (2017-09-07 23:49 MW 8.2), (in Spanish).

[5] Instituto de Ingeniería-UNAM (2017): *Reporte preliminar*. Parámetros del movimiento del suelo, sismo de Tehuantepec (MW 8.2), 7 de septiembre de 2017 (in Spanish).

[6] Meli-Piralla R (1994): Structural design of masonry buildings: The Mexican practice. *ACI special publication 147 masonry in the Americas*, American Concrete Institute, 239-62.

[7] Tena-Colunga A, Juárez-Ángeles A, Salinas-Vallejo VH (2009): Cyclic behavior of combined and confined masonry walls. *Engineering Structures*, **31**, 240-259.

[8] NTCM-04 (2004): Normas Técnicas Complementarias para Diseño y Construcción de Estructuras de Mampostería. *Gaceta Oficial del Distrito Federal*, octubre (in Spanish).

[9] Alcocer SM, Tena A, Berrón R, De la Torre O, Del Valle E, García F, López O, Martínez E, Miranda E, Pavón VM, Tejeda J (1997): Chapter 10: Estructuras de mampostería y adobe. *El macrosismo de Manzanillo del 9 de octubre de 1995*, Arturo Tena Colunga, editor, Sociedad Mexicana de Ingeniería Sísmica and Universidad de Colima, first edition, October, ISBN 968-6190-83-X, pp. 233-267 (in Spanish)

[10] Reyes C, Flores L, Alcocer SM, Lang A, Durán R, López O, Pacheco MA, Juárez H, Martín del Campo R, Tejeda J, Echavarría A, Cuenca J (2006): Chapter 6: Housing, The Tecomán, México, Earthquake January 21, 2003. *An EERI and SMIS Learning from Earthquakes Reconnaissance Report,* Sergio M. Alcocer and Richard E. Klingner, Editors, March, ISBN 1-932884-08-4, 109-190.

[11] Tena A, Martínez J, Gómez A (2014): Comportamiento de la vivienda en México durante el sismo El Mayor-Cucupah del 4 de abril del 2010. *Revista Internacional de Desastres Naturales, Accidentes e Infraestructura Civil*, **14** (1-2), 127-148 (in Spanish).

[12] Ruiz A, Silva G, De León A, Nazar M, Vidal F (2011): Obtención de características geométricas y mecánicas del ladrillo de barro recocido de Tuxtla Gutiérrez, Chiapas. *Quehacer Científico en Chiapas*, **1** (12), 14-26 (in Spanish).

