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# DAMAGES PATTERNS IN HISTORICAL TEMPLES OF PUEBLA, MORELOS AND OAXACA AFTER SEPTEMBER 2017 MEXICO EARTHQUAKES

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**Abstract.** *A brief description of the damages observed after the occurrence of the September 2017 earthquakes in some temples located in the states of Oaxaca, Puebla and Morelos is presented. A total of 48 temples were visited where we observed partial or total collapses of structural elements as: towers, roofs, buttresses, walls and arches in the temples. In some cases, the level of the damage was so severe that compromised the stability of the temples.*

## 1 INTRODUCTION

During September 2017, two high intensity earthquakes hit the central and southern region of Mexico. At 23:49:17 local time on September 7, 2017, an earthquake of magnitude Mw 8.2 occurred in the Gulf of Tehuantepec, 133 km southwest of Pijijiapan, Chiapas and 700 km from Mexico City. According to the National Seismological Service (SSN), this earthquake was catalogued as a normal fault [1]. The maximum acceleration recorded near to the epicenter (PGA) was over 2.28 m/s$^2$ [2]. Serious damage was reported in the states of Oaxaca, Chiapas and Tabasco; mainly to housing, ancient buildings and some infrastructure facilities.

On September 19, a second strong earthquake with a magnitude Mw 7.1 was felt at 13:14:40 local time. The epicenter was located between Puebla and Morelos states, 12 km southeast of Axochiapan, Morelos and 120 km from Mexico City. According to the SSN [3], the earthquake was a normal fault intraplate with a maximum acceleration recorded over 2.20 m/s$^2$, measured near to the epicenter area [4].

According to Meli [5], 2,340 historical buildings suffered some kind of damage, due to the occurrence of the September earthquakes. Table 1 shows the number of heritage buildings damaged in the different states by both September earthquakes, as well as the level of damage reported by the National Institute of Anthropology and History, INAH [6]. INAH established three levels of damage: minor, moderate and severe. In general, minor damage refers to damage without effect in structural elements; moderate damage is when the damage is present in some structural elements but without represent a risk to structural safety of the buildings; the severe damage is when the damage affects the structural safety of part or all of building.

**Table 1:** Number of heritage buildings damaged by the earthquakes [5]

| City | Type of damage | | | Total damaged buildings | Percentage of damaged buildings compared to the total |
|---|---|---|---|---|---|
| | Severe | Moderate | Minor | | |
| Chiapas* | 21 | 29 | 64 | 114 | 4.9 |
| Ciudad de México | 51 | 65 | 81 | 197 | 8.4 |
| Guerrero | 11 | 41 | 43 | 95 | 4.1 |
| Hidalgo | 2 | 6 | 5 | 13 | 0.6 |
| Estado de México | 52 | 135 | 92 | 279 | 11.9 |
| Morelos | 122 | 84 | 53 | 259 | 11.1 |
| Oaxaca | 34 | 308 | 245 | 587 | 25.1 |
| Puebla | 125 | 335 | 161 | 621 | 26.5 |
| Tabasco | 1 | 2 | 24 | 27 | 1.2 |
| Tlaxcala | 11 | 12 | 111 | 134 | 5.7 |
| Veracruz | 1 | 2 | 11 | 14 | 0.6 |
| Total | 431 | 1019 | 890 | 2340 | 100 |

**Note. The building damages only corresponds to the earthquake of September 7*

Only three entities: Oaxaca, Puebla and Morelos concentrated 62.7% of the total damages. Of these, Oaxaca and Puebla represented just over half of the damages (51.6%). For this reason, a campaign of reconnaissance of damages was performed in order to assessment the damage in historical temples in these states. A total of 48 temples were visited (Fig. 1): 22 in Oaxaca, around of the *Mixteca Alta* and Tehuantepec regions; 11 inside of the *Mixteca* region, Puebla; 15 in Morelos, along of the route called *Ruta de los Conventos*. Some of them are included on the World Heritage List of the UNESCO, as "Earliest 16th Century monasteries on the slopes of Popocatepetl". The damage observed is describe in this paper; according to the type of structural element of the temple. For this purpose, the temples were divided into: façades and bell towers; domes and vaults; side walls and apse.


**Figure 1:** Location of the temples visited after the earthquake of September 19, 2017

## 2 FACADES AND BELL TOWERS

The damages observed into the façades were produced mainly due to higher levels of shear stresses into the plane of this element. These damages were displayed with the formation of diagonal cracks and/or with the separation of the main body of the facade or the separation of the side walls. However, some damages were associated with an out-of-plane behavior. Mainly, due to the overturning of the frontispiece and belfries. The bell towers were one of the most damaged elements. In most cases, partial or total collapse of the bell tower bodies was observed.

Some examples are showed in figure 2. The façade of Tlaquiltenango temple, in Morelos, present a separation between the façade and sidewalls; as well as, a diagonal crack in the middle of this element (Fig. 2a). In Tlayacapan, some diagonal cracks were located over the façade, near to the door and windows. The bell gable showed a partial collapse due to the out of plane behavior of this element (Fig. 2b). A similar behavior was observed in the *Sagrario* temple, in Huajuapan de León, Oaxaca (Fig. 2c). The façade of Chila de la Sal chapel showed some cracks between the side walls, in the middle, and the towers (Fig. 2d).

a)  b) 

c)  d) 

**Figure 2:** Damages patterns in façades: a) Tlaquiltenago, Morelos; b) Tlayacapan, Morelos; c) Huajuapan de León, Oaxaca and d) Chila de la Sal, Puebla

The towers were the structural element that more damages presented in temples located, mainly, in Puebla and Morelos. In San Andrés de la Cal chapel, Morelos, the arches of the lower body of the bell tower collapsed and horizontal cracks appeared in the upper and base of the pilasters (Fig. 3a). Similar behavior was observed in the pilasters of the bell towers of Santa Ana Jolalpan (Fig. 3b) and Pilcaya, (Fig. 3c) Puebla.

a)  b)  c) 

**Figure 3:** Damages patterns in bell towers: a) San Andrés de la Cal, Morelos; b) Santa Ana Jolalpan, Puebla c) Pilcaya, Puebla

The temples Hueyapan, Jiutepec and Ocuituco located into the *Ruta de los Conventos*, in Morelos, they have only a one bell tower. In all cases, this element presented a different level of damage, from only cracks until partial or total collapse (Fig. 4). Hueyapan tower shown cracks upper and the base of the pilasters of the first body of the belfry. This is because the upper body, being more rigid and smaller, worked mainly as a rigid body with a considerable mass, where the seismic shear was concentrated (Fig. 4a). The temples of Jiutepec and Ocuituco presented collapses of the bell towers, while the main walls of the facades had slight damage, which was concentrated in the opening of the window of the choir (Figs. 4b and 4c).

a)  b)  c) 

**Figure 4:** Damage to facades of temples in Morelos: a) Hueyapan; b) Jiutepec; c) Ocuituco

Although most of the temples in Mexico have a vaulted roof, as stone o brick masonry, some façades were damages due to presence of the out of plane behavior. For example, in Pilcaya (Fig. 5), the facade was separated from the vault because a deficient anchoring of the roof to the facade wall. Likewise, the frontispiece collapsed due to movement out of plane. In Tlayacapan (Fig. 6) vertical cracking are showed between the façade and the side walls of the nave, due to an out-of-plane behavior.

a)  b) 

**Figure 5:** Temple of Pilcaya, Puebla: a) turning of the frontispiece; b) separation of the facade from the body of the nave

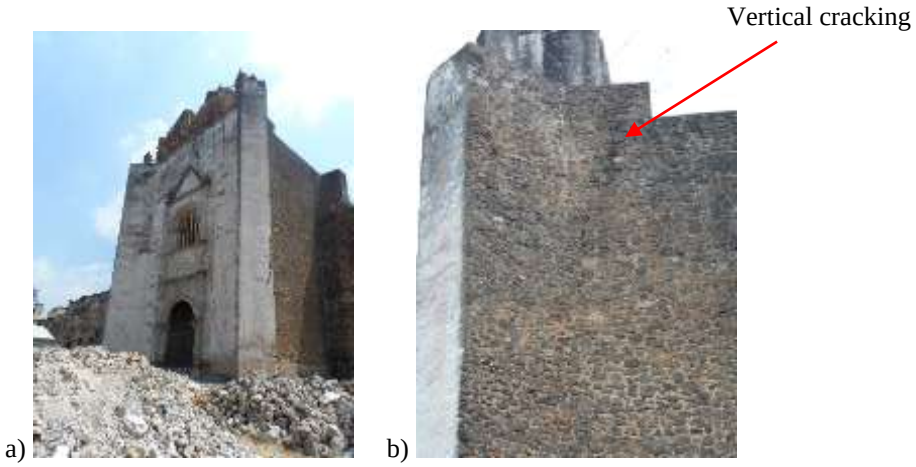


**Figure 6:** Facade of the Tlayacapan temple, Morelos: a) General view; b) Vertical cracking between the facade and the wall of the nave

## 3 ROOFING SYSTEM

The roofing system of this kind of temples is mainly made by domes and vaults. The most common are the barrel vaults without or with lunettes. Many cases of damages in this system was observed, from longitudinal and transversal cracks until partial or total collapses. Figure 7 shows the typical cracking of continuous barrel vaults, where longitudinal cracks are present along the vault. Usually a crack appears at the top of the vault, in the intrados and extrados, ridding the fillings that commonly cover the kidneys of the vault in the extrados (Fig. 7). In some cases, the cracks were large enough to cause the collapse of the vault and arches.

a)  b) 

**Figure 7:** Damage in vaults: a) Tlayacapan, Morelos and; b) Tlaquiltenango, Morelos

About of the domes, typical damages were observed: radial cracks at the base of the dome and meridians on the body of the dome (Fig. 8). In some cases, the damages were located only in the drums. In others, the dome collapsed and the drum remained standing, apparently undamaged (Fig. 9).

**Figure 8:** Radial and meridian cracks in the dome of the Jiutepec temple, Morelos

a)  b) 

**Figure 9:** Damage to the main dome in temples in Morelos: a) Totolapan (sail vault); b) Zacualpan

## 4 SIDE WALLS AND APSE

The temples are massive structures. The weight of their structural elements contributes to the stability. The walls usually are robust and can hardly collapse. However, damage may occur mainly by shear forces that the masonry cannot resist as shown in figure 10.

a)  b) 

**Figure 10:** Damage in side walls: a) El Calvario temple, Huajuapan, Oaxaca; b) Ayoxutla, Puebla

In some cases, the side walls have horizontal cracks that cross the thickness of the wall and generally are located below the windows (Fig. 11). This type of cracking is due to bending moments outside the plane of the wall; which occur mainly in churches that have other bodies attached to the side wall, such as convents, chapels or parish offices. These attached bodies function as struts on the side walls.

**Figure 11:** Horizontal wall cracks in the temple of Tlayacapan, Morelos

Buttresses with added sections at different stages of construction collapsed by separating mainly in areas with old cracks that had been repaired in previous works. In flying buttresses, shear cracks occurred even when their arches had been bricked up, in addition to the separation of the walls (Fig. 12).

a)  b)  c) 

**Figure 12:** Typical damage to buttresses in Morelos: a) Tlayecac; b) Tlayacapan and c) Totolapan

## 5 CONVENT BUILDINGS

The convents buildings visited have a central quadrangular cloister, with one or two levels, surrounded by arcades with or without buttresses, and halls covered by masonry vaults or wooden roofs. They were built during the 16$^{th}$ century. The damages were located in the cloister arches and the roofs of the halls, as well as the walls and vaults of the rooms.

The barrel vaults in the corridors showed longitudinal cracks, located at the top and in the kidneys of the roof; in a few cases they were located in the bases of the vault, as in the Totolapan convent (Fig.13a). These cracks are located frequently next to the cloister, because in this side, the structural elements are insufficient to contain the thrust of the vault, compared to the opposite side, that contain the walls of the rooms, which are more rigid (Figs. 13a and 13b).

a)  b)  c) 

**Figure 13:** Typical damages in Morelos convents: a) Ocuituco; b) Jiutepec; c) Totlolapan

In some convents, the arches of the upper cloister collapse because they have an important opening and the poor quality of the material building. In particular, the convents of Jiutepec and Totolapan, located in Morelos, were the most affected. In the first, the roof of the high cloister was formed by wooden and tiles, with thickness arcades and without buttresses (Fig. 14a). In Totolapan, the damage was associated to the poor quality of the masonry, maybe for a lack of maintenance. The low cohesion between the mortar and the stone induce the crumbling of the masonry, which caused the collapse of the buttressed arch and the barrel vault in the gallery of the high cloister, due to movement out of plane (Figure 14b).

a)  b) 

**Figure 14:** Damage to the upper cloister of Morelos convents: a) Jiutepec; b) Totolapan

The convent of Jantetelco presented severe damage due to the low resistance of the masonry used for its construction; since it is made mostly of large pebbles and a low quality mortar, causing an inadequate adherence between the mortar and the stone as well as for the poor interlocking between the stones. Due to this, when the action of the earthquake induced high levels of stresses on the convent, the masonry crumbling. Figure 15 shows the cloister with debris of the masonry.

**Figure 15:** Damage to the cloister of the convent of Jantetelco, Morelos

## 6 BEHAVIOR OBSERVED IN PREVIOUSLY REINFORCED TEMPLES

Actually, it is difficult to find a temple without any process of intervention realized. In some cases, these interventions are visible and others are hidden. When the intervention is associated to improve the structural response of the temple, the earthquakes are the best test to evaluate the effectiveness of the intervention. During the visits of recognition of damages, some temples structurally intervened were find. Regardless if the intervention was made according to the criteria of conservation of Heritage buildings or not, some cases are presents.

In Oaxaca are located some temples intervened with massive reinforced concrete elements, because they were severely damaged for previous earthquakes. Figure 17 shows two cases: Santiago Cacaloxtepec and San Andrés Dinicuiti, both with reinforced concrete elements embedded in the walls and the vault (Figure 16 and 17). In San Andrés Dinicuiti, the original vault was replaced totally by a reinforced concrete slab (Figure 17b). In both temples, not damages by the earthquake of the September 19 were detected.

a)  b) 

**Figure 16:** Temple of Santiago Cacaloxtepec reinforced with concrete element: a) walls and b) vault

a)  b) 

**Figure 17:** Temples of San Andrés Dinicuiti reinforced with concrete elements: a) walls and b) vault

Other cases were found where only the interventions of reinforcement were applied locally in specific structural element, without intervening adjacent elements. Causing that the damages were transferred to weakest regions that probably before the intervention had not been damages. For example, Figure 18 shows the damage in the drum of the Huajuapan Cathedral. In this case, the dome was rebuilt previously with reinforced concrete. Another example is when reinforced concrete or steel elements are incorporated as structural reinforcement. However, due to incompatibility of materials or an inadequate anchorage with around structural elements, some damages were produced as show in Figure 19.

**Figure 18:** Damage in the dome of Huajuapan Cathedral, Oaxaca due to interventions before to the 2017 earthquakes

a)  b) 

**Figure 19:** Wall collapses due to interventions with concrete slabs in the convent of Jiutepec, Morelos: a) Slab supported directly on the wall; b) Beams supported on the walls

## 7 CONCLUSIONS

The damages reported in this paper correspond to the observed in historical temples of Oaxaca, Puebla and Morelos states due to the earthquakes of September 2017. The damage patterns and mechanisms of collapse described are the same like observed in previous earthquakes. The bell towers, vaults and domes still remain as the most vulnerable elements. Lack of maintenance, poor quality of the masonry, structural modifications and inadequate previous interventions are the main causes of the damages observed in this kind of structures.

Continuous and correct maintenance of the structure is indispensable to reduce the possible damages due to earthquakes. A detailed structural assessment of the temples always is necessary to performance an adequate intervention program according to the criteria of restauration of Heritage Buildings.

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