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SEISMIC ASSESSMENT OF FAÇADES OF MEXICAN COLONIAL CHURCHES

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Abstract. *The seismic assessment of façades of churches built during the colonial era in Mexico is presented. This study takes into account two typologies of churches of the center of Mexico, which are far away of the epicenters of the subduction zone. The first one corresponds to churches built near to local active faults. The second typology corresponds to churches built far away of the local faults and the subduction zone, but they suffer frequent earthquakes. The façades of the first typology are low-rise and have thick walls and some buttresses. The façades of the second typology are taller and slender. Both typologies have only one bell tower. The seismic assessment was obtained by means of non-linear dynamic analyses, by using several real earthquake records. These earthquake records were registered by stations located near and far of the epicenter zone. According to the numerical results, the façades of the churches near of the local faults can support high accelerations with moderate damage. While the façades of the churches built far away of the local faults present considerable damage for medium accelerations. For both typologies, the belfries are the most vulnerable element. As well as, the damage mechanism are different for both typologies. The main difference is that for the second typology, the body of the tower tends to separate of the façade wall, while for the first typology, they tend to remain attached.*

1 INTRODUCTION

Thousands of churches were built in Mexico from 16th to 18th century, and persist to date in rather good conditions. They vary in size and architectural sophistication, but follow some basic typologies. The simplest among them are rather small parochial churches which are found in every town and village of Mexico. One important factor that has influenced the evolution of their architectural features has been the experience of damage suffered from earthquake activity. It is in the area of the Pacific Coast where the recurrent destruction of the early construction produced an evolution towards low rise, heavily buttressed buildings with scarce external ornamentation. In other regions the lower concern for earthquakes failures favored taller and more slender constructions.

The seismic activity of Mexico can be divided in four big zones: A, B, C and D (Fig. 1; [1]). These zones are delimited with base in the frequency of occurrence of the earthquakes in the different regions and the expected maximum ground acceleration in a century. The zone A is a zone where it has not been reported earthquakes in the last 80 years and it is not expected ground accelerations bigger than 10% of the gravity acceleration. The zone D identifies the places where earthquake occurrence is very frequent and the ground accelerations can be higher than 70% of the gravity acceleration. It is here where the historical big earthquakes were registered. The B and C zones are intermediate regions where earthquakes are not registered frequently and the ground accelerations recorded are not greater than the 70% of the gravity.

In 1999, the center and southwest of Mexico were affected by two earthquakes (June and September) of intermediate magnitude (M=7.0). The Tehuacan earthquake of 15 June was a deep-seated intraplate earthquake, having its epicenter inland [2]; while the earthquake of 30 September was a normal faulting event and had its epicenter in the Oaxaca's coast [3]. These earthquakes caused significant damage in masonry structures, including more than 1800 historical monuments. Façades and bell towers were one of the most damaged elements of the churches and the belfries were one of the most common elements which collapsed.

Figure 1: Seismic regionalization of Mexico [1].

In this context, in recent years the study of the seismic behavior of façades becomes an important issue of study [4-6]. Therefore, the aim of the paper is to assess the seismic behavior of façades of churches built in Mexico during the colonial era. The structural behavior of these elements is described and the causes of the most common structural damages are explained. Two typical typologies of churches built in the center of Mexico were considered. The first one corresponds to churches built far of the subduction zone but near to local active faults. The second typology corresponds to churches built far away of the local faults and the subduction zone, but they suffer frequent earthquakes.

2 DESCRIPTION OF THE FAÇADES

At the beginning of the colonial era (16th century), the façades of the churches were a flat wall with two openings. One for the door and the other for the window which illuminated the choir. From the 17th century, churches became more elaborated, higher and with more volume. The façades also changed to more elaborated forms. The frontispiece was higher and the wall had more decoration [7].

The bell towers were not very common elements of the churches during the 16th century. Most of the temples of this century lacked of towers and the bells were set in a bell-gable. In some cases there was a single low rise tower, very robust and of simple architecture. This contrast with the tall slender towers of the churches in the cities of later centuries. It is know that the convent churches of the Franciscan order did not have towers. In many temples, the towers were added in later centuries. There are some examples where the church has a bell tower and a bell-gable [7].

The experience of the ancient builders about the seismic activity of the Country allowed to develop different typologies of churches depending on their location. The center of Mexico (Mexico City and surroundings) is located in the seismic region B (Fig. 1). This area is hit by the earthquakes generated in the Pacific coast, but it israre the earthquake with epicenter in this zone.Thus this study takes into account two typologies of churches of the center of Mexico (Fig. 2). The first one corresponds to churches built near to local active faults which are located at the north of Mexico City (Naucalpan). The second typology corresponds to churches built far away of the local faults, located at the south of Mexico City (Morelos). However both zones suffer frequent earthquakes generated in the Pacific coast. The façades of the first typology are low-rise and have thick walls and some buttresses. The façades of the second typology are taller and slender. Two churches were selected for each typology. Saint Bartholomew Apostol (Barth) and Saint Mary Nativity (Nativitas) correspond to the first typology; while Ocuituco and Tetela del Volcan (Tetela) are of the Morelos typology (Fig. 3).

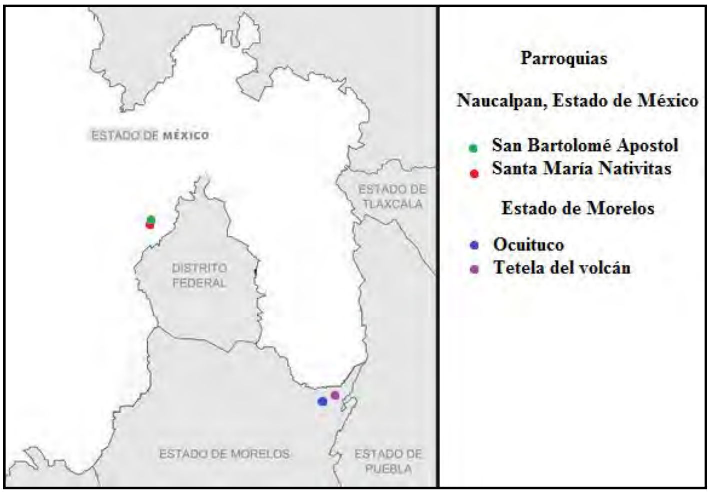


Figure 2: Localization map of the studied churches.

Table 1 summarizes the dimensions of the four selected façades. It can see that the façades of the first typology are smaller than the second typology. The height of the bell tower is almost the half of the height of the second typology.

Figure 3: Façades of: a) Barth; b) Nativitas; c) Ocuituco; d) Tetela.

Table 1: Façades geometry (dimension in m).

Element	Dimension	Barth	Nativitas	Tetela	Ocuituco
Façade	Length	17.68	11.19	18.25	17.90
Central Wall	Height	10.5	9.02	15.29	14.85
	Thickness	0.85 – 1.0	0.66 – 1.2	1.3 – 1.9	1.2 – 1.7
Bell Tower	Height	13.4	13.44	21.7	20.86
	Base	5.2 x 4.26	3.03 x 3.27	5.5 x 5.17	5.55 x 4.99
Belfries	Number	2	1	2	2

3 TYPICAL DAMAGES OF FAÇADES

Façade is typically a tall and heavy wall, poorly connected to the rest of the temple. However, the key damages have shown that the main behavior of these elements is in the plane of the façade. The out-of-plane behavior is generally less important and is only regarded with the detachment of the façade from the nave, but without reach the collapse [8]. This is mainly due to the presence of the towers, built in an integrated manner with the façade and not simply constructed in compliance. In fact, these towers provide a constraint that reduces the movement out-of-plane, but also increase the in-plane actions, and are also committed themselves to a combined bending and torsion stresses (Fig. 4). In the same way, the slab of the chorus restrains the wall and reduces the façade slenderness. Thus, the shear actions have a significant role in the damage patterns, especially in the joints between the façade and towers [5, 6].

Bell towers are rather slender and weak elements, in which the effect of ground motion is greatly amplified. Even if they are relatively low and sturdy, their failure is rather common, especially in the vertical elements and in the arches surrounding the belfry. Additionally, their bending motion tends to separate them from the rest of the church, or to generate shear cracking in the lower body of the tower.

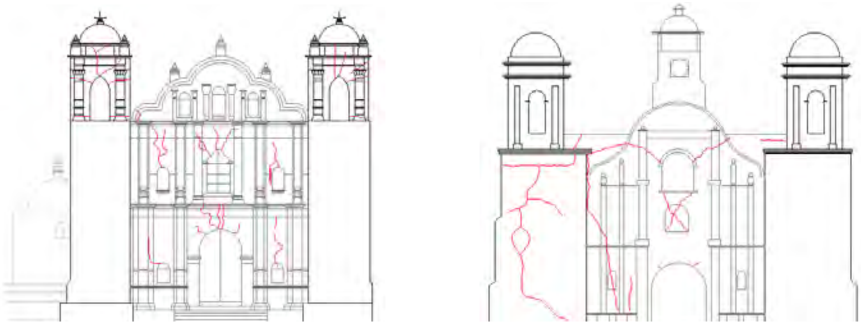
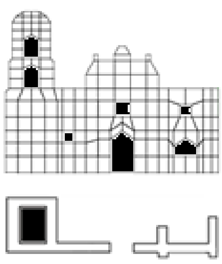
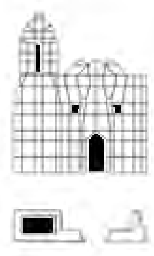
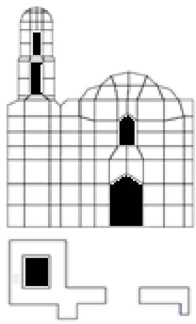
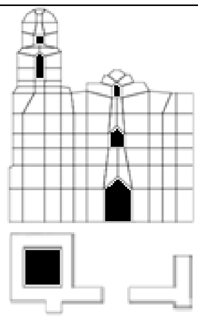


Figure 4: Typical damages on Façades

4 NUMERICAL MODELS OF THE FAÇADES

The key damages in the façades are in-plane, while the out-of-plane behavior is generally less important and is only regarded with the detachment of the façade from the nave. In this context, the seismic behavior of the façades is studied considering only the in-plane response by means of a rigid element model (Table 2). The Rigid Element Method idealizes the masonry structure as a mechanism made of rigid elements and springs, allowing fast non-linear dynamic analysis of masonry structures [9].The basic construction material of these historical buildings is a masonry conglomeratecomposed of stones of different sizes, agglutinated by a lime-sand mortar. Lightweight stonesof volcanic origin were preferred by builders. Thisheterogeneous masonry can be considered a kind of low-strength concrete.Table 3 shows the mechanical properties of the masonry material [6], which was equal for the four façades models.The models were calibrated considering the modal shapes and periods of the Barth's façade. The reference values were taken from full 3-D model [6].

Table 2: Rigid element model of the façades (relative scale)

Barth	Nativitas	Ocuituco	Tetela
			
Nodes: 207 Elements: 148 DoF: 444	Nodes: 189 Elements: 145 DoF: 435	Nodes: 150 Elements: 108 DoF: 324	Nodes: 143 Elements: 97 DoF: 291

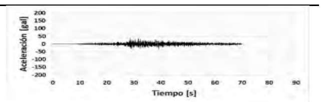
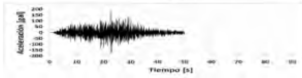
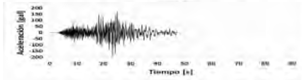
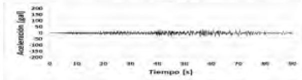
In order to study the seismic behavior of each façade, four different real seismic records were used. These records differ in place, magnitude, duration and peak ground acceleration. Table 4 summaries the main characteristic of each record. The greatest peak ground acceleration was recorded on the event of July 15 at Cd. Serdán; however, it has the shortest duration.

Otherwise, the seismic record of the same station on September 30 has the longest duration, but the lowest peak ground acceleration. Records 2 and 3 were registered near the epicenter, while record 1 and 4 were registered far away of the epicenter (around 200 km). The seismic event of 15 June was an intraplate earthquake, while the event of 30 September was a subduction earthquake.

Table 3: Mechanical properties of the masonry.

Property	Value
Mass density ρ	1600 kg/m^3
Elastic modulus E	0.36GPa
Poisson's coefficient v	0.1
Compressive strength $f'c$	1,500 kPa
Tensile strength ft	70 kPa
Cohesion c	50 kPa
Friction angle ϕ	25°
Shear modulus G	0.164 GPa

Table 4: General characteristics of the seismic records used.

Record	Site	Duration (s)	PGA (gal)	Magnitude (Mw)	Epicenter	Date	Accelerogram
1	Oaxaca	70.0	38	6.5	Puebla	15-06-99	
2	Oaxaca	50.0	186	7.5	Oaxaca	30-09-99	
3	Cd. Serdán	47.5	195	6.5	Puebla	15-06-99	
4	Cd. Serdán	96.4	34	7.5	Oaxaca	30-09-99	

5 SEISMIC ASSESSMENT

In order to assess the seismic behavior of the façades; three different analyses were performed: own weight; modal analysis and non-linear dynamic analysis. Each one gives important information about the structural behavior of the façades, as well as the differences among themselves.

5.1 Own weight

Table 5 shows the total weight of the façades, as well as the average axial stress in the foundation. As it can see, the Morelos typology (Ocuituco and Tetela) are heaviest façades than Naucalpan typology (Barth and Nativitas). This difference is almost four times. However, the difference in the average axial stress at foundation is almost only two times. This is due to the difference in the thickness of the walls (see Table 1). Safety factor is 10 and 6 for Naucalpan and Morelos typology, respectively. This level of vertical stresses due to own weight is common in the colonial churches in Mexico [10].

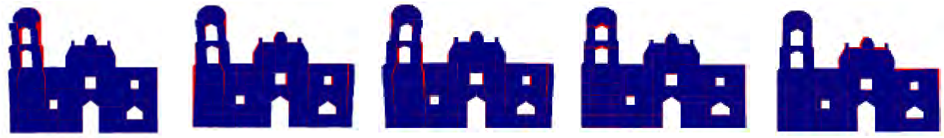
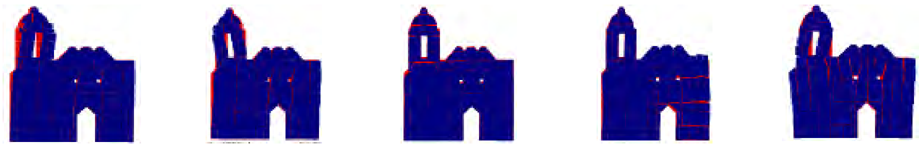
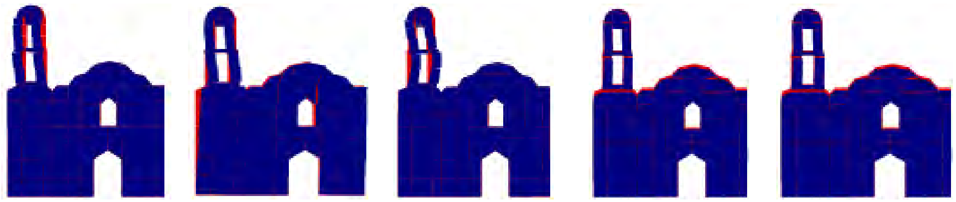
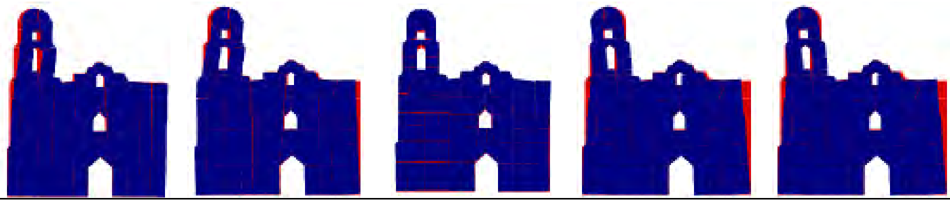
Table 5: Results of the own weight analyses.

Façade	Total weight (kN)	Base Area (m^2)	Average axial stress (MPa)	Safety Factor
Barth	3724.46	29.90	0.14	10.83
Nativitas	2390.24	14.45	0.17	9.07
Ocuituco	9042.82	37.15	0.24	6.16
Tetela	9985.97	39.82	0.25	5.98

5.2 Vibration modes

Table 6 shows the periods and the modal shapes for the first five modes of vibration for each model. Periods are higher in the churches of Morelos. This is mainly due to the height of the belfries. In all cases, the first period is only due to a vibration of the belfries and the second period is a combination of the lateral motion of the façade with the vibration of the belfry in contra-phase. The third mode for Barth and Ocuituco churches is the second lateral mode; while for Nativitas and Tetela is the first vertical mode. Fourth mode is vertical; for Barth and Ocuituco is the first vertical mode, while for Nativitas and Tetela is the second one.

Table 6: Periods and modal shapes.

Façade	1	2	3	4	5
Barth	T=0.2692s	T=0.1379s	T=0.0983s	T=0.0842s	T=0.0763s
					
Nativitas	T=0.2381s	T=0.1281s	T=0.0911s	T=0.0721s	T=0.0558s
					
Ocuituco	T=0.5660s	T=0.2646s	T=0.1338s	T=0.1235s	T=0.1157s
					
Tetela	T=0.3542s	T=0.1880s	T=0.1298s	T=0.1130s	T=0.1069s
					

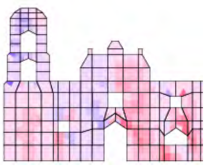
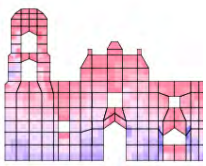
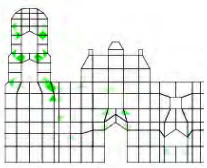
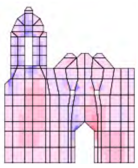
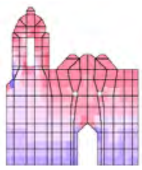
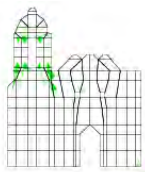
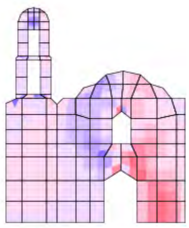
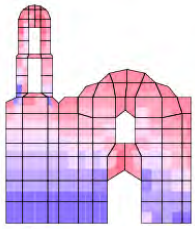
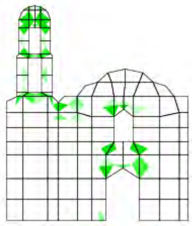
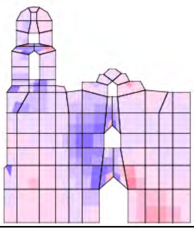
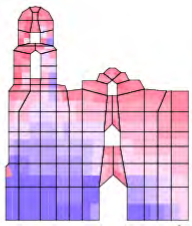
5.3 Non-linear dynamic analyses

Non-linear dynamic analyses were performed by using the seismic records of Table 4. Only the results of records 2 and 3 are presented here since they are the most critical. Table 6 and 8 present the maximum displacement of each model for records 2 and 3, respectively. Due to the great stiffness of the façades, small displacements were obtained. It is clear that the greatest displacement was registered at the top of the belfries. It can see that the maximum displacement at the tower is different than the wall of the façade. This means that the tower tends to detach of the main wall. On the other hand, the displacement at the frontispiece is almost the same than the displacement at the top of the wall; which means that there are practically not amplification of the displacement due to the great stiffness of the façade. However, the amplification of the displacement at the top of the belfries is around four times to the displacements at the frontispiece.

Table 6: Seismic record 2: Maximum Displacement (mm).

Façade	Tower	Wall of the façade	Frontispiece	Belfry at top	Time (s)
Barth	3.27	3.35	3.38	14.61	24.05
Nativitas	5.23	3.90	4.05	18.00	22.79
Ocuituco	8.18	10.13	10.18	25.49	30.01
Tetela	6.48	5.36	5.35	20.24	29.35

Table 7: Seismic record 2: deformed shape and maps of stresses and damage.

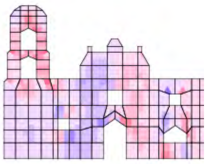
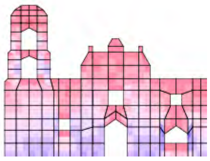
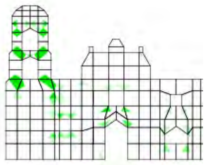
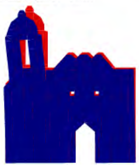
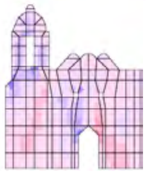
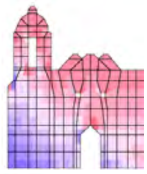
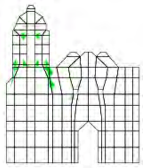
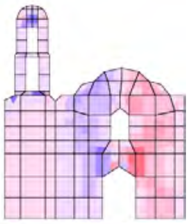
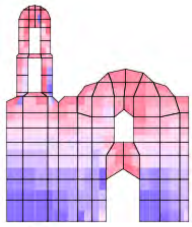
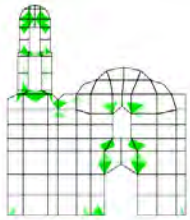
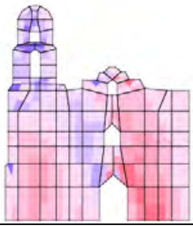
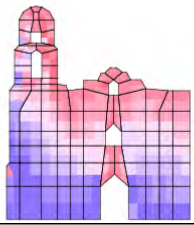
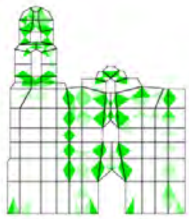
Façade	Deformed shape	Shear stresses	Vertical axial stresses	Tensile damage
Barth				
Nativitas				
Ocuituco				
Tetela				

Deformed shape and the maps of shear and vertical stresses are shown in Tables 7 and 9, as well as the tensile damage for each façade. It is worth to note that there is no damage due to compressive and shear stresses. The damages presented in the façades are due to tensile stresses. Damages are concentrated on the belfries which are the most vulnerable element of the façade. It can see that the tower tends to detach of the façade due to flexural behavior. This behavior is according to the observed damages. The most vulnerable façade is Tetela; while the belfry of Ocuituco is the most vulnerable of the four façades.

Table 8: Seismic record 3: Maximum Displacement (mm).

Façade	Tower	Wall of the façade	Frontispiece	Belfry at top	Time (s)
Barth	3.68	3.39	3.40	27.12	24.13
Nativitas	5.27	3.97	4.12	10.10	24.42
Ocuituco	11.49	11.35	11.20	47.01	19.75
Tetela	20.39	14.71	12.36	40.46	24.70

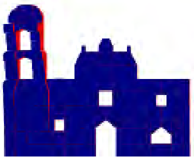
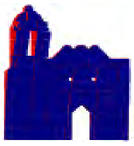
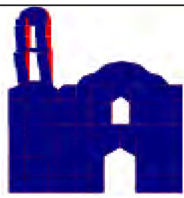
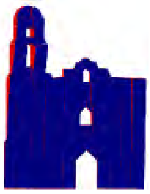
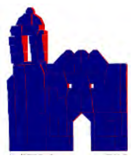
Table 9: Seismic record 3: deformed shape and maps of stresses and damage.

Façade	Deformed shape	Shear stresses	Vertical axial stresses	Tensile damage
Barth				
Nativitas				
Ocuituco				
Tetela				

5.4 Final vibration modes

One simple way to observe the influence of the damage in the seismic behavior of the structures is by means of the changes of the dynamic properties of the structure. Therefore, at the end of the non-linear dynamic analysis, the vibration modes were recalculated by considering the change of the stiffness due to damage. Table 10 shows the comparison among the initial vibration modes and the final vibration modes. The percentage of the change in the period (A) is also shown in Table 10. The modal shapes do not change, thus the first mode of vibration continues to correspond to the vibration of the belfries.It can see that the Nativitas façade has only light damages as the enlarged of the first period is only 2%. On the other hand, the most damaged façade is Tetela due to the seismic record 3, while Ocuituco has the biggest damages due to seismic record 2.

Table 10: Initial and final vibration modesobtained with records 2 and 3.

Analysis	Barth	Nativitas	Ocuituco	Tetela
Initial	 T=0.2692s	 T=0.2381s	 T=0.5660s	 T=0.3542s
Record 2	 T=0.2991 s A=11.10%	 T=0.2440 s A=2.50%	 T=0.6228 s A=10.05%	 T=0.3743 s A=5.68%
Record 3	 T=0.3071 s A=14.06%	 T=0.2438 s A=2.40%	 T=0.6063 s A=7.13%	 T=0.4373 s A=23.45%

6 CONCLUSIONS

- The seismic behavior of façades of churches built during the colonial era in Mexico was studied.
- Two representative typologies of churches of the center of Mexico were considered.
- The first one corresponds to churches built near local faults (Naucalpan), while the second one was built far away of local faults (Morelos). Both typologies are located far away of the subduction zone.
- Two seismic events were considered in the analyses. One corresponds to an intraplate earthquake, while the second was a subduction earthquake.
- Morelos typology is more vulnerable than Naucalpan typology. Because they are slender and heavier façades.
- The most vulnerable element is the belfry which has an appendix like behavior.

- The towers tend to detach of the façade. This behavior is according to the observed damages.
- It is interesting that churches built near local seismic faults are lower and more robust than churches built far away of seismogenetic zones. This could be due to the experiences of the ancient builders about the seismic activity of the different zones.

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