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Seismic Assessment of Bell Towers of Mexican Colonial Churches

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Abstract The seismic assessment of bell towers of churches built during the colonial period in Mexico is studied. Two representative typologies of churches of the southwest of Mexico are considered. The results of non-linear static and the non-linear dynamic analyses are compared. The results show that it is not recommended the use of non-linear static analyses; being necessary the use of full non-linear dynamic analyses.

Keywords: Tower, façade, bell tower, church, vulnerability

Introduction

The earthquakes have been one of the main causes of destruction of the architectural heritage buildings, especially those which are placed in the regions of high seismic risk. The careful seismic assessment of the architectural heritage affected by severe earthquakes is one of the most effective ways to understand structural weaknesses of those constructions.

The churches built in Mexico during the colonial period, between the 16th and 18th centuries, vary in size and in architectural style; however, it is possible to find a general basic typologies. An important factor which influenced the architectural style was the experience of the ancient builders due to the seismic activity of the country. Generally, in the Pacific's coast and more specifically in the States of Oaxaca and Puebla, the recurrent destruction of the first constructions caused an evolution of the churches towards edifications of not much height, with big buttresses and little outer ornamentation. By this reason, the churches of Oaxaca are rectangular, with one nave and a simple façade that has attached one or two small towers. On the other hand, regions where the seismic activity is smaller, the churches remained higher and slender. It is the reason why the churches of Puebla are bigger, with a plant of Latin cross. Its façades have also attached one or two towers; which are approximately twice higher than towers of Oaxaca's churches (Fig. 1).

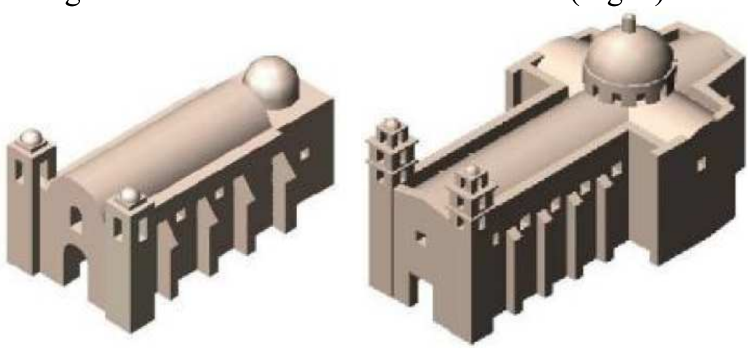

Figure 1: Typical colonial churches from south western of Mexico; State of Oaxaca (left) and Puebla (right)

The seismic activity of Mexico can be divided in four big zones for analysis and design: A, B, C and D (Fig. 2; CFE, 2003). 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 regions where earthquakes are not registered frequently and the ground accelerations recorded are not greater than the 70% of the gravity.

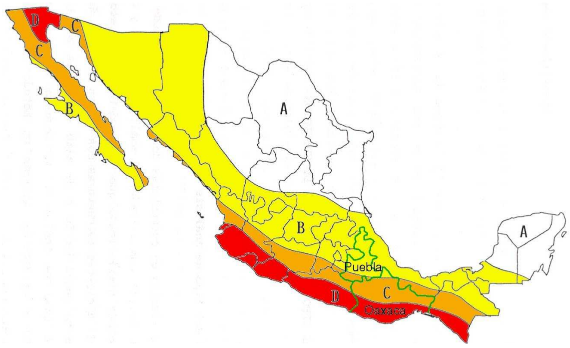

Figure 2: Seismic zones of México

In 1999, the center and southwest of Mexico were affected by two earthquakes (June and September) of intermediate magnitude (M=7.0). The earthquake of 15 June was a deep-seated intraplate earthquake, having its epicenter in Tehuacan (Pestana et al. 2002); while the earthquake of 30 September was a normal faulting event and had its epicenter in the Oaxaca's coast (Hernandez et al. 2001). These earthquakes exceeded the limits established by the spectrum of design and caused significant damage in masonry structures, including more than 1800 historical monuments. The bell towers were one of the most damaged elements of the churches and the belfries were one of the most collapsed elements.

According to these facts, the main objective of this research is to assess the seismic behaviour of bell towers; where the structural behaviour of these elements is described and the causes of the most common structural damages is explained. In this context, two typical churches of the Mexican southwest were considered for the study of the seismic assessment of the bell towers. The first one corresponds to the state of Oaxaca (zone D) and the second typology corresponds to the churches built in the state of Puebla (zone B).

Typical Damages in Bell Towers

Observation and evaluation of seismic damage suffered by typical stone masonry historic churches have allowed to identify their basic modes of failure and main characteristics of seismic response: the behaviour is governed by the low tensile strength of constituting materials, which makes it almost impossible to provide continuity within and between structural members, and leads to specific mechanisms for resisting seismic actions.

Façade is typically a tall and heavy wall, poorly connected to the rest of the temple. Its vibration out of plan tends to separate it from the rest of the temple. Horizontal cracking in the frontispiece, or in the lower part of the façade weakened by large openings, is rather common, sometimes giving rise to the partial or total overturning of the façade. However, the bell towers are rather slender and weak elements, in which the ground motion is greatly amplified. Even if they are relatively low and sturdy, their failure is rather common, especially in the vertical elements and 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 basement of the tower.

After the earthquakes of 1999, damage surveys of churches from the states of Puebla and Oaxaca was made by different institutions. It was possible to recover reliable data from 172 churches: 142 from Oaxaca and only 30 from Puebla. It must to bear in mind that this number is not the total of churches damaged by the 1999 earthquakes. From statistic study of the damages presented in those 172 temples, the 88% of the churches (152) were damaged in the bell towers, being one of the most vulnerable elements. From this total (152 churches), the 90% showed damages in the belfry, 88% in the body of the tower, whereas only the 10% were damaged in the small dome of the belfry. It is worth to note that the sum gives more than 100% because some churches presented combined

damages. From the total of the churches damaged in the belfries (137), the 77% were damaged on the arches and architraves of the belfries; while the 42% showed damages on the pillars. The total collapse of the belfries was 8% (11 temples), while the partial collapse was 15% (20 churches).

On the other hand, from the 134 temples that were damaged in the basement of the tower; 53% was vertical damage, 27% was diagonal and 20% was horizontal damage. The horizontal and diagonal damage is due to flexural behaviour and to shear forces, respectively. The vertical damage is due to horizontal tensile stresses that cause the detachment of the vertical elements (walls) and not due to the material crushing (excessive compressive stresses). From the total of the churches that showed vertical cracks in the basement (67 temples): the 15% presented cracks on the joint between the tower and the wall of the nave; the 38% on the union between the façade wall and the tower; and the 70% presented the vertical cracks in the body of the tower .

Numerical Models for the Seismic Assessment of Bell Towers

The key damages in the bell towers have shown that the main behaviour of these elements is in the plane of the façade. The out-of-plane behaviour is generally less important and is only regarded with the detachment of the façade from the nave (Alcocer et al. 1999). In this context, the seismic behaviour of the towers is studied considering only the in-plane response. Two typical churches are considered. The first one corresponds to the state of Oaxaca whose height of the belfry is around 4 m; being the total height of the tower of 14 m (Fig. 3). The second typology corresponds to the churches of Puebla; the total height of its bell towers is 28 m high. The height of the belfry is around 10 m. Due to the stiffness that present the façades, it is thought that the acceleration of the closest seismic sources can cause more damage.

Two Rigid Element models were considered; which correspond to the typical churches of the states of Oaxaca and Puebla (Fig. 3). 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. For further details about the method please refer to Casolo and Peña (2007). The Oaxaca's church façade model has 264 elements and 792 degrees of freedom, whereas the Puebla’s church has 237 elements and 711 degrees of freedom. The mechanical characteristics of the masonry material are: modulus of Elasticity (E) = 1962 MPa; Poisson´s ratio (v) = 0.20; Density of mass (ρ) = 1600 kg/m3; Compressive strength (f’c) = 2943 kPa; Tensile strength (ft) = 294.3 kPa; Cohesion (c) = 353.2 kPa; Friction angle (ϕ) = 15° (Meli and Peña 2005).

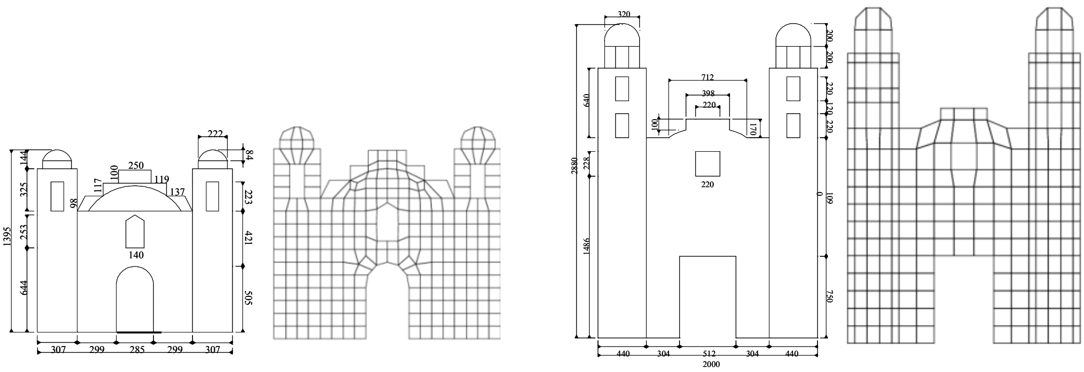

Figure 3: Dimensions and rigid element models of façades of colonial churches south – western Mexico; State of Oaxaca (left), and Puebla (right)

Non-Linear Static Analysis

A set of non-lineal static (pushover) analyses was carried out considering that the lateral forces are proportional to the mass of the elements (constant acceleration). Fig. 4 shows the capacity curves and the mechanism of collapse for both models. The spectra of pseudoacceleration – displacement for the zones B, C and D are also depicted. This method, through a graphical procedure, compares the capacity of the structure and the seismic demand. The capacity of the structure is defined by a

capacity curve, while the seismic demand is represented by a reduced design spectrum. This methodology defines the maximum displacement that demand to a structure as the intersection point of the curve of capacity and the spectrum of design.

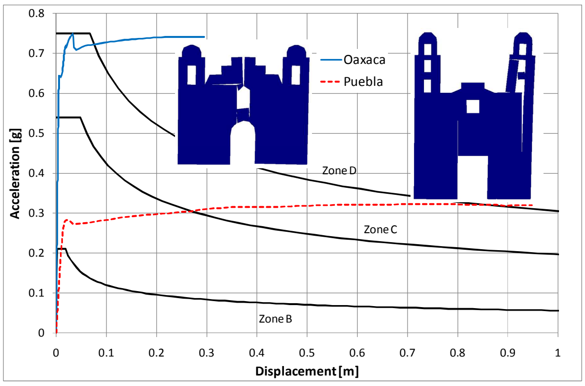

Figure 4: Capacity curves and design spectra for zones B, C and D

According to Fig. 4, the model of Oaxaca is more resistant than the model of Puebla. The maximum acceleration that models could resist is 0.75g and 0.32g, for Oaxaca and Puebla respectively. Both models present elastic – linear behaviour for the accelerations of the spectrum of zone B. For the zone C, the model of Oaxaca would resist without any damages the acceleration of the design spectrum; while it would present a slight damage for the zone D. The model of Puebla would present moderate damages with the acceleration of the spectrum of zone C and would be close to the collapse in the zone D.

The collapse mechanism of the Oaxaca's façade corresponds to a vertical crack that crosses the central part of the façade (the door and the window of the chorus) causing that the façade will be divided in two macroelements. In this way, each tower remains attached with a part of the façade. Thus, each macroelement presents a flexural behaviour of the whole part. On the other hand, in the model of Puebla only one tower is damaged. A vertical crack along the body of the tower is presented, as well as the belfry presents damages due to flexion.

However, this type of damage is not similar as the damages observed during the earthquakes of 1999 for this type of elements. This is due to those curves do not reproduce the real behaviour of the structure; because the intrinsic limitations and hypotheses with they were built. As for example, the behaviour of this type of façades cannot be simplified as a system of one degree of freedom due to the big influence of higher modes has in the seismic response of the structure. Therefore, it is not recommended the use of this type of analysis for the study of bell towers.

Non-Linear Dynamic Analysis

Five synthetic records compatible with the design spectra for each one of the seismic zones B, C, D were generated. Both models were analysed for each one of the three zones. Fig. 5 presents the damage obtained due to the dynamic analysis for the models of Oaxaca and Puebla; as well as the deformed shape at the instant that the models present the maximum response. The main damage was by tension due to the belfry flexion. The body of the tower presents damage by shear forces, only for the Puebla model. Both models did not present compressive damage, in any element.

The church of Oaxaca is extremely rigid so the towers do not present practically displacements for the accelerations of zones B and C. The maximum displacement obtained at the top of the towers was of 0.1, 0.5 and 2.0 cm, for the zones B, C and D respectively. The model does not present any damage with the spectrum of zone B, while the same model presents slight and moderate damage, for zones C and D respectively. The damage is due to flexion in the pillars of the belfries, as well as a cracking in the central part of the façade, which crosses the window of the chorus and the main door. The walls present a horizontal cracking at the base of the towers due to the flexural behaviour of the whole structure. It is worth to note that the damage is mainly on the towers for both models.

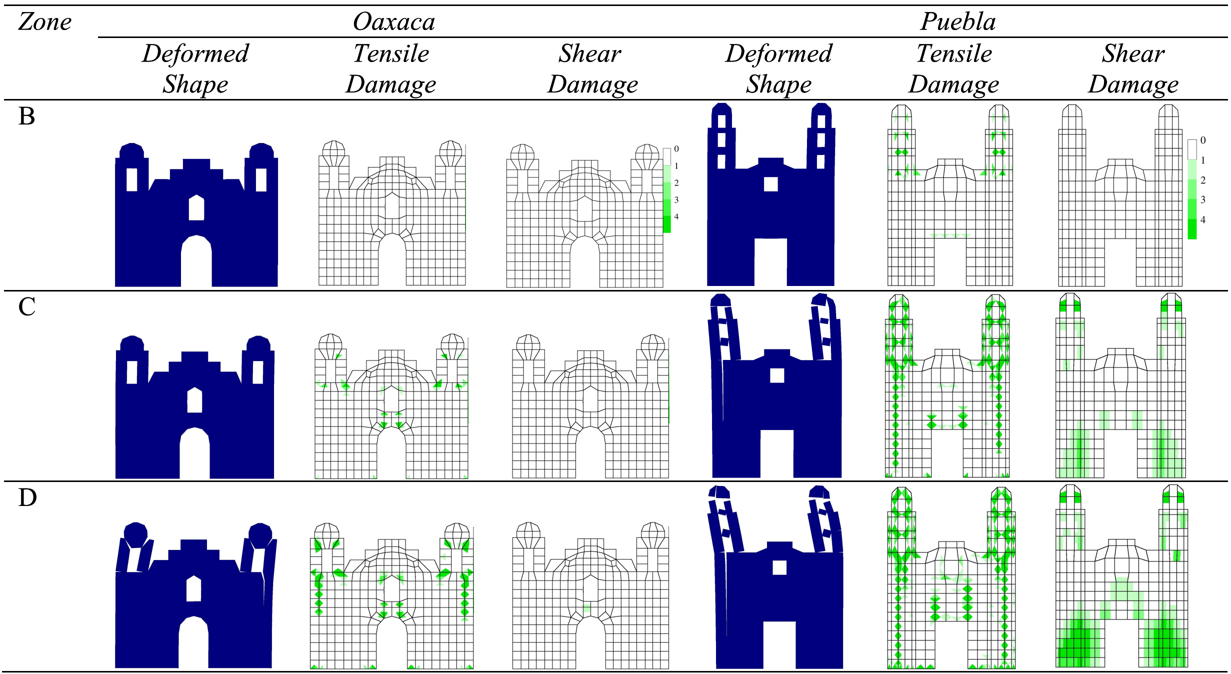

Figure 5: Deformed shape and damages for the Oaxaca's and Puebla's model due to a compatible record with the design spectra for zones B, C and D

On the other hand, the belfry of the Puebla model is much more flexible. The final displacement of this model is greater than the Oaxaca's model due to the tower heights. The belfry presents a maximum displacement of 1, 9 and 17 cm for the zones B, C and D, respectively. The belfry presents an appendix like behaviour, amplifying the seismic motion. For this typical case, the towers present moderate damage for the zone B, and high damage for the zones C and D. A vertical crack along the body of the tower and shear damage in the basement exist too.

Table 1: Maximal seismic coefficient and hysteretic dissipated energy

Zone	*Maximum seismic coefficient*		*Hysteretic dissipated energy*		
	Oaxaca	*Puebla*	*Oaxaca (kJ)*	*Puebla(kJ)*	*Oax/Pue(%)*
B	0.11	0.12	0.00	17.48	0.00
C	0.42	0.26	4.70	167.45	2.80
D	0.55	0.31	11.51	579.23	1.99

Table 1 shows the maximal seismic coefficient and hysteretic dissipated energy. It is worth to note that for the same zone, the records cause amount of damage different for both models. For example, for the zone B the seismic coefficient is the same for both models but the dissipated energy is grater for Puebla's model. Otherwise, for the zone D, maximal seismic coefficient of Oaxaca is grater that Puebla but the dissipated energy is less.

The type of damage obtained with both models is quite similar to the damages observed during the earthquakes of 1999: horizontal cracking at the base and at the top of the pillars of the belfry and a vertical crack in the body of the tower.

Final Remarks

The seismic assessment of bell towers of churches built during the colonial period in Mexico was presented. Two representative typologies of churches of the southwest of Mexico were considered. The first typology was from the state of Oaxaca, which is highly seismic zone. The second typology is from the churches built in the state of Puebla, localized around 250 km from the subduction zone.

The results of non-linear static analyses and the non-linear dynamic analyses were compared. The static analyses predicted bigger resistances than the dynamic analyses. This is due to the influence of the superior vibrating modes in the dynamic behaviour of the towers. In this case, the belfries have an appendix like behaviour that increases the accelerations. Therefore, it is not recommended the use of non-linear static analyses for the study of bell towers; being necessary the use of non-linear dynamic analyses.

The types of damages obtained with both models, using synthetic records compatible with the design spectra, are quite similar to the damages observed during the earthquakes of 1999: horizontal cracking at the base and capital of the pillars of the belfry and a vertical cracking in the body of the tower. Therefore, the belfries were the most vulnerable elements in the towers. This coincides with the statistical study from the damages due to the earthquakes of 1999.

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