Dynamic Behavior of Puebla City Cathedral

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SUMMARY:
This study analyzes a stone masonry Cathedral in Puebla, Mexico which is a World Cultural Heritage. In order to guarantee its safety a dynamic analysis of the structure was made through a finite element model. To reproduce the real dynamic behavior of the Cathedral, the model was calibrated using the vibrating modes obtained from noise records taken on the structure and processed by spectral ratios on Sac2000 software. Modes of failure and the critical stress zones obtained from the model will be use to reinforce the building and to reduce its seismic vulnerability.

Keywords: Dynamic behavior, stone masonry, dynamic analysis, noise records, historical buildings

1. INTRODUCTION

Mexico has a lot of historical buildings, built in the colonial times, XV-XVIII centuries, mostly made of stone masonry. Some of them unfortunately have not survived over the years due to seismic events that have caused their collapse.

Figure 1. Location of Puebla City Cathedral

One of the most emblematic and beautiful buildings that have survived, is the Cathedral of Puebla City built from 1575 to 1768. Puebla State is located in the center of Mexico and despite of the existent distance is affected by earthquakes caused by the subduction of the Cocos Plate under the North American one (see Figure 1). However, Puebla is not only affected by earthquakes originated in the subduction zone, also it is affected by intraplate earthquakes those which have caused severe damage to historical buildings (e.g. June 1999. Tehuacán, Puebla. Magnitude [M] = 7.0). This is why it is necessary to analyze the dynamic behavior of the cathedral to ensure its preservation.

2. STRUCTURAL ANALYSIS

For studying the response of the cathedral during seismic events, it is necessary to create a model that simplifies in the best way, the real behavior of the structure. This model requires the knowledge of its geometry, of the mechanical properties of its structural elements and of the seismic forces that take place in our model.

It is very important to define the type of modeling to represent the real behavior of the structure. In our case, the Cathedral of Puebla is a stone masonry building. It is known that masonry is a heterogeneous and anisotropic material, whose mechanical characteristics depend on the mechanical and geometrical characteristics of the materials that comprise them.

Due to the anisotropy of the masonry, the domain of resistance is function of the direction in which the principal stresses are presented relative to the direction of the mortar joints. That is why the numerical approximation can be based on micro models, in which the pieces and the mortar are discretized separately or in macro composite models in which the units, and interface boards are represented on the same element with homogenized properties, located throughout the element.

The linear analysis is the simplest analysis where it is assumed that both the material and structural system have a linear elastic behavior. Even though the behavior of masonry is non-linear, linear analysis can be used to determine the behavior of the structural system for low stress levels. Considering the maximum stresses is possible to identify areas where cracking can occurs. Thus with all the information obtained with a preliminary model, it will be possible to create new models that use this information to know the whole behavior of the structure. Furthermore, from this analysis is possible to obtain de modal modes of vibration.

The seismic behavior of historic buildings is more complex than the behavior of actual buildings made of steel and concrete due to multiple factors, highlighting the following: uncertainty in the continuity of the elements, the deterioration that has suffered the materials over time and the lack of maintenance All these factors can cause, during significant seismic events, significant damages or the partial collapse of these historical structures.

2.1 Structuring of the Cathedral

The cathedral has a nave of 97.67 meters long by 51 meters wide, forming a Greek cross. It has 14 colossal Doric columns nearly 15 meters high from the base to the capital. All 6 fluted pilasters with the same height support the vaults and arches of the upper nave. Another 18 columns embedded in the side walls of 9.78 meters capital base have to support the nave vaults below. All the pillars bear the weight of forty-two domes, all vaults are made of gray stone that was brought from the neighbor villages of the city and carved with a precision that seems to work without any error.

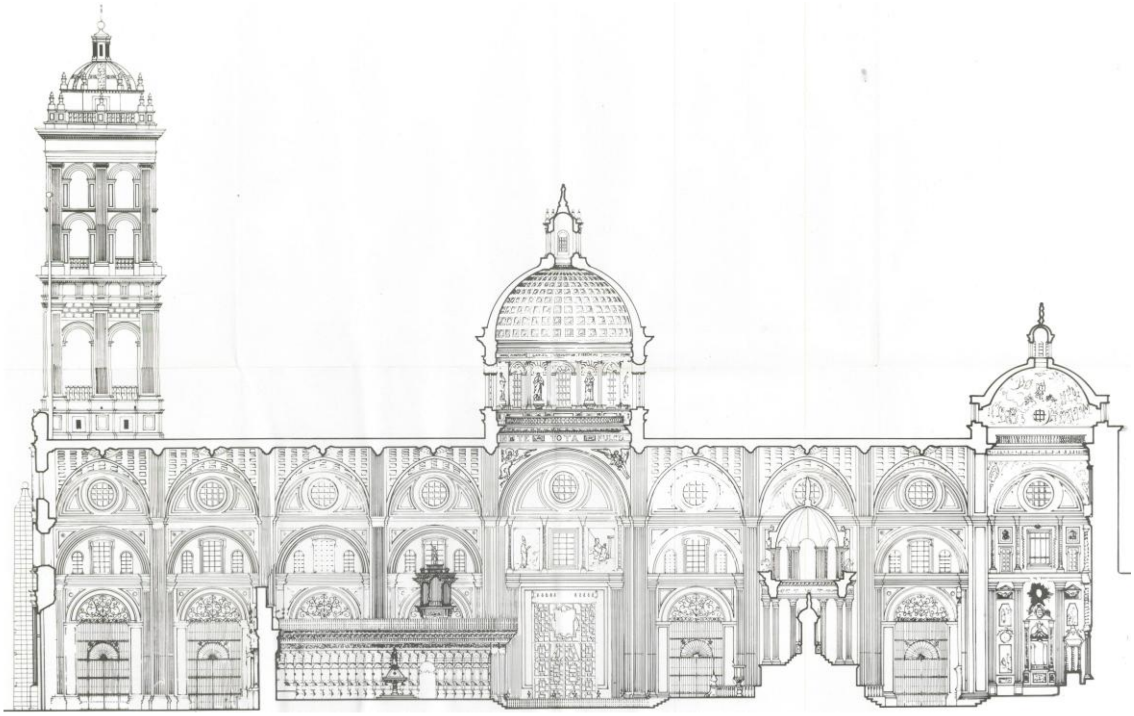

Figure 2. Longitudinal court of the structure

The 14 isolated columns that form the middle nave are not circular, however they form a square post with a column embedded in each face, taking this into account this concept is that you are a total of 74 columns and six pilasters. They support 12 visible arches and 4 hidden, having a total of 30 sight and 4 embedded in the main walls.

The cathedral has two towers. The north tower, also called the old tower was completed in 1678 and is the only one with bells. The south tower was built later on the year of 1731 and completed in 1768. Both are 70 meters high

3. DEVELOPMENT OF STRUCTURAL MODEL OF THE TEMPLE

The development of an analytical model of a three-dimensional structure requires the following steps:

- ✓ Development of a geometric model of the structure, in this case the lifting geometry.
- ✓ Development of a model of the structure in three dimensions
- ✓ Identification and selection of the type of finite element to be used in the model number
- ✓ Discretization of the model using the selected item type
- ✓ Identification of material properties and its application to the model.
- ✓ Application of load conditions.
- ✓ Application of boundary conditions.
- ✓ Solution of the model.
- ✓ Review and interpretation of results.

The structural system of the model was made by shell elements for its easy way of use; a 3D model was formed in order to know the mode shapes of the whole structure. This model consists of macro-elements that can be use to analyze separately each of the structural elements that form the Cathedral of Puebla.

Within the mechanical properties taken to the modeling are presented in next table:

Table 3.1. Material Properties used in the FEM

Material	Density (Ton/m^3)	Poisson´s ratio	Young´s modulus (Ton/m^2)
Masonry 1	2	0.16	200,000
Masonry 2	2	0.16	500,000

The initial model consisted of 7589 shell elements and 6891 nodes. Through this initial analysis it was possible to identify the vibration modes. On the other hand the study of the dynamic behavior will be the basis for correcting defects in the elaboration of the model.

The first 20 modes were obtained from the 3D model. These modes are shown below.

Table 3.2. Modal Periods and Frequencies

OutputCase	StepType	StepNum	Period	Frequency	CircFreq	Eigenvalue
Text	Text	Unitless	Sec	Cyc/sec	rad/sec	rad2/sec2
MODAL	Mode	1	0.753576	1.327	8.3378	69.519
MODAL	Mode	2	0.748308	1.3363	8.3965	70.502
MODAL	Mode	3	0.672997	1.4859	9.3361	87.163
MODAL	Mode	4	0.664225	1.5055	9.4594	89.481
MODAL	Mode	5	0.358765	2.7873	17.513	306.72
MODAL	Mode	6	0.352338	2.8382	17.833	318.01
MODAL	Mode	7	0.29879	3.3468	21.029	442.21
MODAL	Mode	8	0.27493	3.6373	22.854	522.29
MODAL	Mode	9	0.263789	3.7909	23.819	567.35
MODAL	Mode	10	0.254408	3.9307	24.697	609.96
MODAL	Mode	11	0.230463	4.3391	27.263	743.29
MODAL	Mode	12	0.224978	4.4449	27.928	779.98
MODAL	Mode	13	0.221308	4.5186	28.391	806.05
MODAL	Mode	14	0.210103	4.7596	29.905	894.32
MODAL	Mode	15	0.206777	4.8361	30.386	923.33
MODAL	Mode	16	0.199522	5.012	31.491	991.7
MODAL	Mode	17	0.191497	5.222	32.811	1076.6
MODAL	Mode	18	0.183414	5.4522	34.257	1173.5
MODAL	Mode	19	0.174482	5.7313	36.011	1296.8
MODAL	Mode	20	0.1724	5.8005	36.445	1328.3

4. CALIBRATION OF THE MODEL WITH ENVIRONMENTAL VIBRATION

The vibration frequency of any construction is an important factor that determines other calculations related to seismic current norms, knowing the natural frequency of the construction and applying the design spectrum the basal shear can be obtained. The spectral ratios obtained using the horizontal component divided by the vertical in a record taken on the ground, depends on the assumption that the spectral amplitudes of the vertical component of motion is relatively insensitive to the effects of site, containing mainly the effect of the source and the attenuation at along the path of the source station, so obtaining the ratios between horizontal to vertical components of motion (H/V), the effects of attenuation and the source are eliminated from the horizontal component leading to the effect of the site, as proposed by Nakamura in 1989 and applied in 1993 by Chavez-Garcia Palermo.

In this study the method uses horizontal components of motion for any floor of the building divided by the reference spectrum which is the spectrum of the base (L/L and T/T). In this case the technique used to obtain the periods of the structure is based on the hypothesis that the movement of the floor is the same as the original input motion at the base of the building. So, by dividing the two components of motion on the structure [N-S and E-W] between the base floor, eliminating the effect of source and route of the noise record, it will lead to know the response of the selected floor of the structure.

4.1 Signal processing

To record noise from de structure, two accelerometers Kinemetrics Altus K2 were used, each one connected to a Kinemetrics episensor and adjusted to 100 samples per second.

A total of 25 records were taken of which 3 of them were placed in each of the towers at different levels to observe its behavior, 11 recordings were taken on the roof of the cathedral and 11 points on the ground, inside and outside of the cathedral to use records and perform longitudinal and transverse spectral ratios (L / L) and (T / T) and thus to define the modes of vibration of the cathedral.

All records have a duration of 900 s. Each record was processed by using the software Seismic Analysis Code (SAC2000), using segments of 30 seconds and performing spectral ratios.

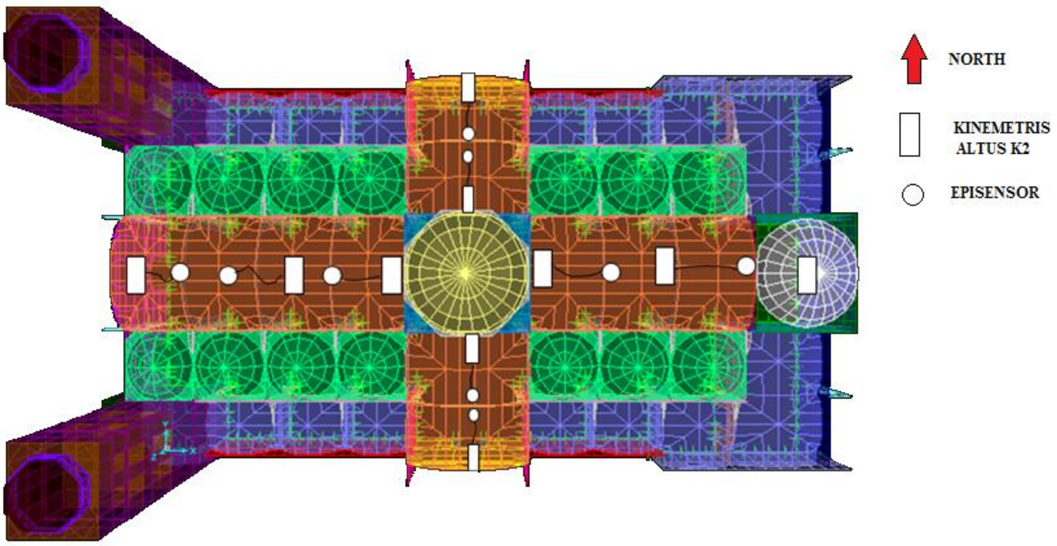

Figure 3. Location of the accelerometers on the structure roof

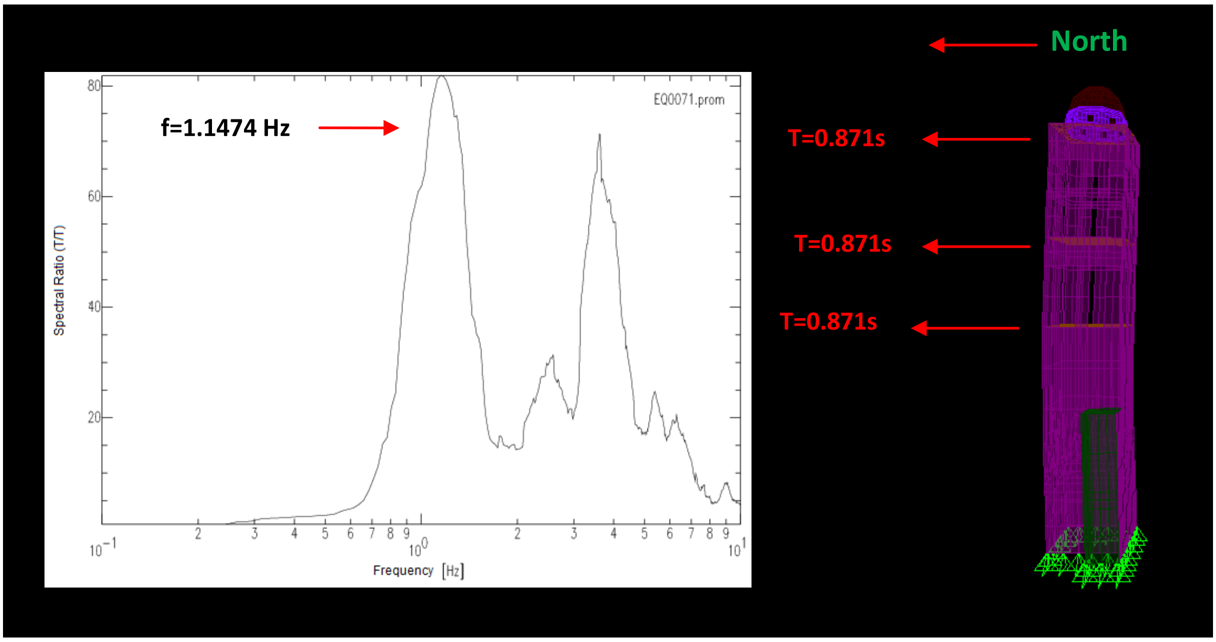

Figure 4. North Tower.
Vibration periods obtained at different elevations. On the left, transfer function from spectral ratio (T/T)

In the next table are the principal results of the environmental vibration analysis:

Table 4.1. Modal Periods and Frequencies

Element	Frequency (Hz) N-S	Frequency (Hz) E-W	Period (s) N-S	Period(s) E-W
North Tower	1.1475	1.2451	0.87	0.8
South Tower	1.22	1.2451	0.819	0.8
Nave	2.56	2.73	0.39	0.366

To ensure the results, response spectrums were used in conjunction for the above elements.

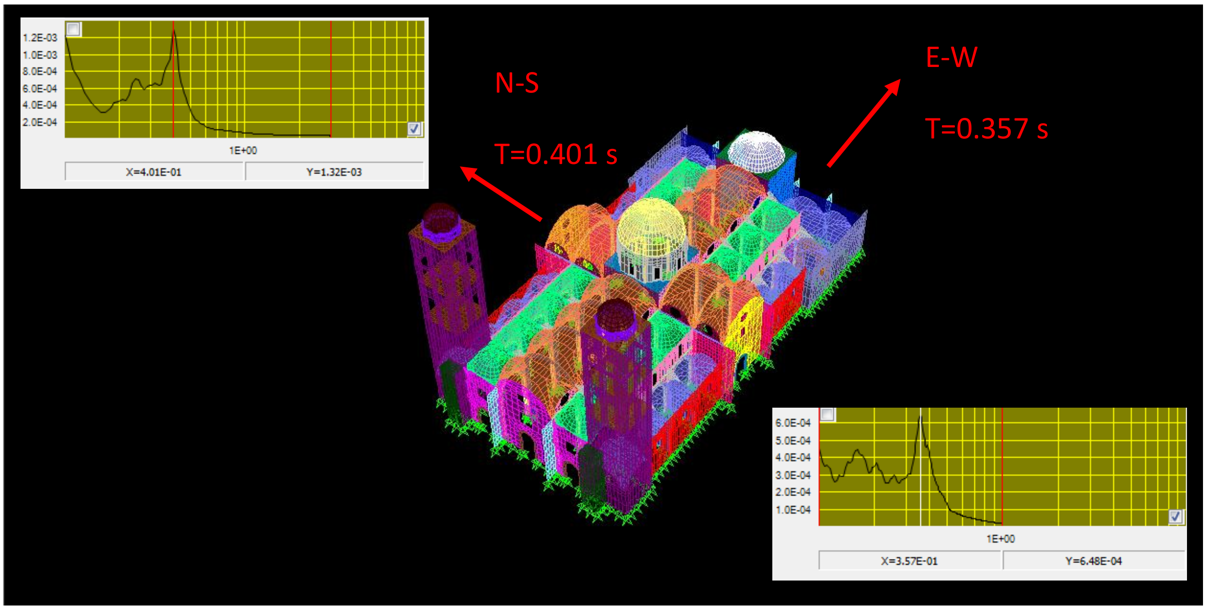

Figure 5. Periods of the nave obtained from response spectrums

We present a comparative table of the periods obtained from spectral ratios and response spectrums.

Table 4.2 Comparisons of periods obtained from Spectral ratios and Response Spectrum techniques

Element	Spectral Ratios		Response Spectrum		Difference (%)	
	Period (s) N-S	Period(s) E-W	Period (s) N-S	Period(s) E-W	N-S	E-W
North Tower	0.87	0.8	0.871	0.78	.001	2.5
South Tower	0.819	0.8	0.83	0.77	1.3	3.75
Nave	0.39	0.366	0.401	0.357	2.7	2.45

After analyzing the results obtained by the spectral ratios and response spectrums we found that both techniques gave us an accurate mode shape of the cathedral so we can proceed to calibrate our model. Making a comparison between the periods obtained from finite element model and determine the environmental vibration, our model is more rigid than our actual structure so we proceed to change the Young modules. In addition, to have greater accuracy it was decided to increase the number of shell elements. So in our calibrated model we obtain the following results.

Table 4.3. Modal Periods and Frequencies

OutputCase	StepType	StepNum	Period	Frequency	CircFreq	Eigenvalue
Text	Text	Unitless	Sec	Cyc/sec	rad/sec	rad2/sec2
MODAL	Mode	1	0.873754	1.1445	7.191	51.711
MODAL	Mode	2	0.868508	1.1514	7.2345	52.337
MODAL	Mode	3	0.78268	1.2777	8.0278	64.445
MODAL	Mode	4	0.773658	1.2926	8.1214	65.957
MODAL	Mode	5	0.391753	2.5526	16.039	257.24
MODAL	Mode	6	0.385064	2.597	16.317	266.25
MODAL	Mode	7	0.332184	3.0104	18.915	357.77
MODAL	Mode	8	0.313964	3.1851	20.012	400.5
MODAL	Mode	9	0.297885	3.357	21.093	444.9
MODAL	Mode	10	0.294526	3.3953	21.333	455.1
MODAL	Mode	11	0.291449	3.4311	21.558	464.77
MODAL	Mode	12	0.28529	3.5052	22.024	485.05
MODAL	Mode	13	0.26073	3.8354	24.098	580.74
MODAL	Mode	14	0.245316	4.0764	25.613	656
MODAL	Mode	15	0.237154	4.2167	26.494	701.94
MODAL	Mode	16	0.227659	4.3925	27.599	761.71
MODAL	Mode	17	0.217307	4.6018	28.914	836.01
MODAL	Mode	18	0.207371	4.8223	30.299	918.05
MODAL	Mode	19	0.198949	5.0264	31.582	997.41
MODAL	Mode	20	0.198102	5.0479	31.717	1006

4.2 Modal information from full 3D model

It is showed the percentage of participation of twenty modes included in the analysis.

Table 4.4. Modal Periods and Frequencies

OutputCase	ItemType	Item	Static	Dynamic
		Text	Percent	Percent
MODAL	Acceleration	UX	97.3006	62.8388
MODAL	Acceleration	UY	97.0814	60.1334
MODAL	Acceleration	UZ	37.3852	8.0038

Since not all the mass take part of each modal mode it is important to say that from the periods obtained of the environmental vibration the first four modes corresponds to the vibration of the towers in both directions, the fifth mode corresponds to the vibration of the nave from North to South (shown in Fig. 6) and the sixth mode from East to West (shown in Fig. 7)

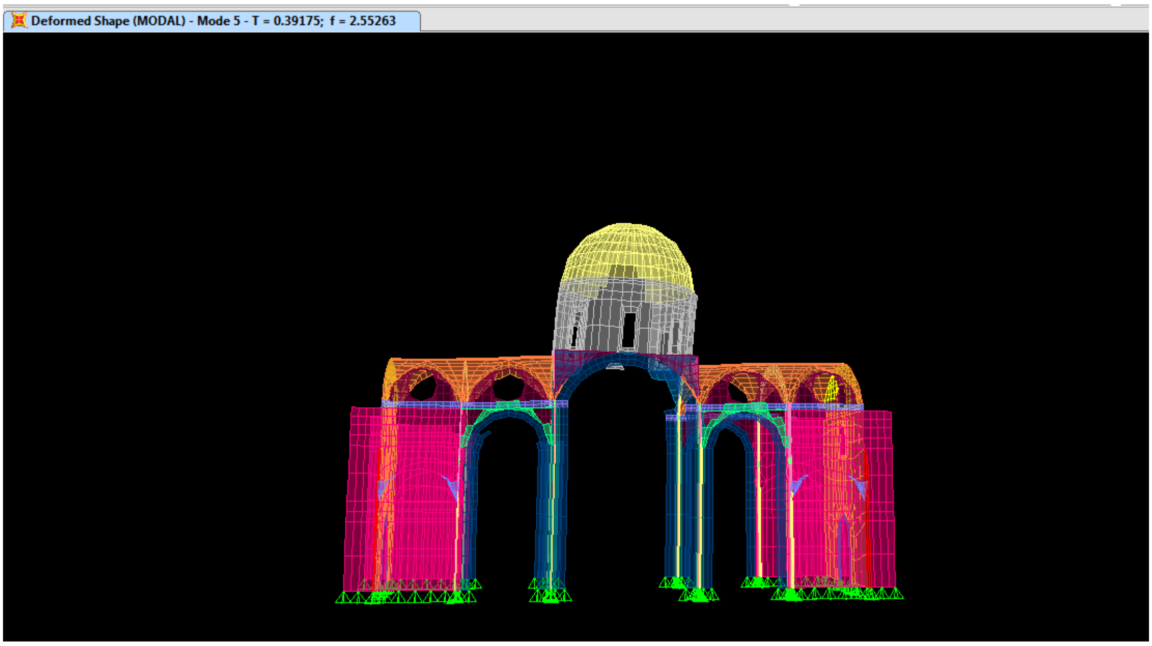

Figure 6. Fifth mode. Movement of the nave from North to South

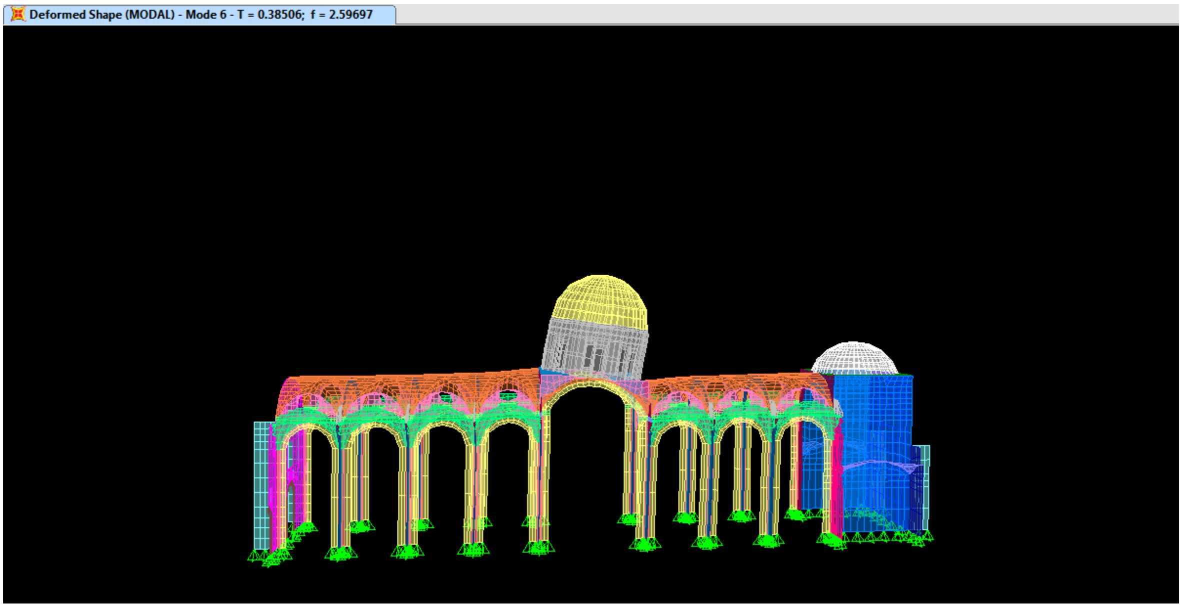

Figure 7. Sixth mode. Movement of the nave from East to West

5. TRIDIMENSIONAL MODEL

For this paper only the analysis for the 3D model will be shown. On this model the next analysis were used:

- ✓ **Static.** Considering the weight of the macro element, formed by the loads of walls and roofs (gravitational).
- ✓ **Modal analysis** considering the gravitational loads and adapting the number of vibration modes of each macro element.
- ✓ Response spectrum analysis using the proposed design spectrum.

6. SEISMIC ANALYSIS

6.1 Seismic Forces

For our analysis a response spectrum analysis was made using the design spectrum proposed in the Supplementary Technical Norm for seismic design of Puebla for a soil type II.

The building is located in zone II according to the seismic zoning map of Puebla City, resulting seismic coefficient of 0.32 for construction of group B, and 0.48 for buildings of Group A in the corresponding spectrum.

7. RESULTS

7.1 Gravitational

Table 7.1 Base Reactions

Output Case	Case Type	Step Type	GlobalFX	GlobalFY	GlobalFZ
			Tonf	Tonf	Tonf
DEAD	Combination		5.013E-09	3.085E-09	65846.0747
SEISMIC X	Combination	Max	19475.8044	6.5371	66463.3769
SEISMIC Y	Combination	Max	6.5293	17041.9887	65228.7725

7.2 Stresses states

The result for the maximum stress is obtained for gravitational forces and for the response spectrum

Table 7.2. Stress states

OutputCase	CaseType	Smax		Smin	
		min	**max**	**min**	**max**
Text	Text	tonf/m2	tonf/m2	tonf/m2	tonf/m2
CMCV	Combination	-105.1	35.45	-24.8	13.1
Seismic X	Combination	-134.7	**76.2**	-67.2	22.2
seismic y	Combination	**-154.2**	48.9	-72.3	34.8

The above table shows that the maximal stresses will appear on a seismic event with approximately values of -154.2 ton/m2 to compression and 76.2 ton/m2 to tension.

8. CONCLUSIONS AND COMMENTS

The first part of the research objective was to develop a model represent the cathedral under the assumption linear elastic behavior for the study of their response to seismic loads, calibrated with environmental vibration from noise records.

The results obtained with the hypothesis describes a linear-elastic initial behavior of the structure without degradation and is satisfactory when the structure is subjected to low levels of effort so further studies are required to consider not linearity of material and structure to meet the same resistance levels last in order to evaluate its safety.

Since the center of the city of Puebla is a world heritage site with more two thousand listed buildings, it is important to develop this line of research, studying the different types, structural systems, materials, construction systems and to perform experiments and numerical simulation in order to preserve the buildings and reduce the seismic vulnerability that currently exists, especially in the case of temples are places where many people gather frequently as the Puebla City Cathedral.

This research was focused to study the global behavior of the temple using shell elements and comparison of different finite element models is a problem that must be raised in further research, when the level of knowledge of the material is sufficient for a more detailed modeling, which allows not scan only the linear elastic hypothesis but also under non-linear hypothesis behavior.

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