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Influence of dominant site period effects on damages at colonial church

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ABSTRACT: Guatemala, due to its geographical position within the complex of tectonic plates, has a diverse geology and a high degree of seismic vulnerability. This happens especially in the areas near the Motagua fault, which is why it is necessary to carry out a geotechnical study in the region of San Raymundo in the Department of Guatemala, as it is classified as a broad area of alluvial landfill. It is in this place where the colonial Church of San Raymundo is located. An experimental analysis of the dominant period of the site was carried out to establish from the soil indicators of the study area, the seismic influence processes, reasons for which a model with fresh adobe blocks was elaborated at scale (1/8.75) and was tested on vibrating table. Records of the San Marcos Earthquake (2012) were used to know the dynamic behavior of the historical structure dating from the fifteenth century. In the earthquake of 1976, the church suffered severe damage in the facade, vault, and side walls.

1 INTRODUCTION

Guatemala has been affected through its history by a series of strong and moderate earthquakes, which have caused considerable human losses and material damage of national consideration at the level of modern infrastructure, traditional and popular structure and a strong impact on our colonial historical monuments, mainly due to the response of the construction materials used in their time and the seismic amplification of the soil, for this reason it decided to carry out a series of evaluations in the area where there is a historical colonial monument with antecedents of seismic affectation and that has presented vulnerability in current conditions, in order to obtain data that help to propose structural and non-structural techniques that mitigate the negative effects on this valuable structure.

For this reason the study was conducted in the Municipality of San Raymundo in the northern part of the municipality of Guatemala, in Region I or Metropolitan Region, with a population of 29,000 inhabitants, classified as acceptable for the study based on the results of the field trips, geotechnical studies and laboratory analysis, which qualify this area prone to generate seismic amplification. For this purpose a mathematical model was made to know the structural dynamic behavior of the Church of San Raymundo and then an experimental model at scale that was capable of being simulated with seismic signals registered in the Seismological Service (in3) and to analyze the damages and faults of the structure. So also make the comparison between the dominant period of the soil with the period of vibration of the structure.

2 SEISMIC BACKGROUND

The seismic threat of San Raymundo and its surroundings can be classified from moderate to high, being confirmed by the serious affectations that have occurred in two histories: 1) Series of strong tremors (swarms) of Guatemala of the years 1917 and 1918, which they were a series of earthquakes that occurred with epicenter in the capital city between December 24, 1917 and May 1918, and that destroyed the city and several municipalities in its surroundings. 2) Severe affectation and destruction in the earthquake of 1.976 with epicenter in the Falla del Motagua (Morales Izabal), to this it is necessary to add that, the population has felt earthquakes of smaller magnitude, which have been incorporated within their customs, owes to the complex of secondary faults to the fault of the Motagua River, which are in its vicinity.

3 SOIL CHARACTERISTICS

3.1 *General geology of the place*

The geology zone of the country is characterized by being a meeting point of ancient basins and topographic and ancient geomorphology. The zone is also characterized by strong depressions, which make it an ideal place of alluvial, wind, lake, and fluvial fillings, as can be seen in the different layers of stratigraphy that can be observed in the zone's ravines and roads. All of this appears on a tertiary base of hard rock where very old deposits of monzonitic granite and some phases of diorite quartz predominate (Figure 1).

3.1.1 *Analysis of soil layers identified for seismic hazard*

It is characterized by presenting a lithology of the surface a towards the interior of the geological base formed in the following way: soil in formation, clay fill with high plasticity, alluvium of facies fillings that has intercalations of granulated pumice sand, pumice strata of the rhyolitic and rhyodatic type and an andesite base in the lower parts, below the classification of the Padre Miguel geological formation (TPM), where rhyolitic tuffs, andesite facies and basalts dominate, some of them hematitic.

3.1.2 *Relationship of the identified soil layers with the existing seismic threat*

Based on the geology of the study area, it has been established that the areas of geological alluvial fill (Table 1), old geomorphological zones of massive depressions, and the tertiary have strongly predominated by means of different origin and mechanics of the same. It is a zone of seismic movements with characteristics of having significant processes of potential wave amplification and other characteristics of compression and wave dilation, they are accentuated on the geomorphology of ancient depressions, consisting mainly of a hard base of ancient deposits and lava flows of monzonitic granite and diorite quartz, which make them

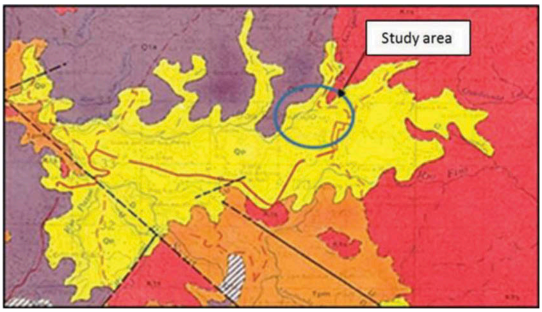

Figure 1. Section of geological sheet San Juan Sacatepéquez, No. 2060 IIG -IGN-.

good conductors of seismic vibrations of the tectonic type, characterized by having interfacial deposits of pumice, little andesite and if many meters of riodacitas ignimbritas.

3.2 *Vulnerability of the area to geological hazards*

According to the geological report and the results of the soil analyzes, it was established that the urban part around the church of San Raymundo, presents vulnerability to be affected by geological risks, such as subsidence, landslides due to the characteristics of the second and third layer of the basement that forms the area on which the town sits where it has physical characteristics of clay-rich strata of the malleable type and low support capacity, according to laboratory data where the internal friction angle reaches 16.52 degrees, Specific weight of 1,733 Tn / cubic meter, humidity percentage of 31.68 and granulometric studies, which confirms that the soil support value tends to be low and therefore has seismic amplification characteristics and the generation of settlements in the infrastructures.

4 SAN RAYMUNDO CHURCH

The Church of San Raymundo is located 31 kilometers from Guatemala City. The church was built in the mid-15th century with local materials and workers from the same community

The Church of San Raymundo is located 31 kilometers from Guatemala City in the Municipality of San Raymundo. The church was built in the middle of the 15th century with local materials and by workers from the same community. It is conformed by walls, arches, buttresses, vault and a dome which were made of adobe masonry and the foundations are made of stone masonry joined with a mixture of clay or lime and sand, Weber (1991). The Church of San Raymundo has a length of 50.95 m, a width of 13.75 m, its facade has a height of 15.70 m, in the upper part of the dome it has a height of 14.75 m and in the vault a height of 11.80 m. The width of the wall is 1.5 m and the dimensions of the buttress are 1.10 x 1.60 m. (Figure 2).

The Church suffered heavy damages such as breakage of the dome, collapse of the vault and damage to the walls and buttresses in the earthquake of February 4, 1976, it was restored at the beginning of 1987, having as objective the conservation of the original structures that still they were within the architectural group, structural members of reinforced concrete were integrated within the interventions.

5 METHODOLOGY

First, a field evaluation was carried out to determine the geological conditions of the study area and to know the lithological columns. Second, the physical and mechanical properties of soils, based on standardized laboratory procedures. Third, the adobe material was analyzed and finally a mathematical and an experimental scale model was made to compare data between them.

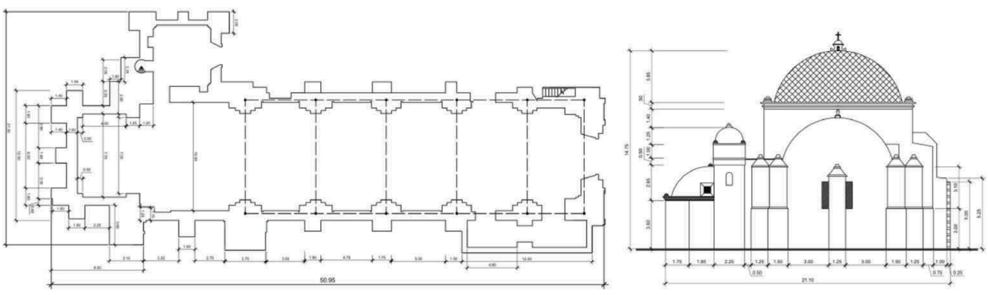

Figure 2. Drawings of San Raymundo Church, Plant (Left) and back facade (right).

6 SITE EFFECT

The location of the triaxial short-period portable sensors used to identify the response of the site effect was placed at a distance of 150 meters from the church due to the urbanity and protection requirements of the historical monument, applying the technique of the spectral quotient H / V, using environmental noise records. The results are a natural ground frequency of 1.9 Hz with an amplification factor of 5.1 and a dominant period of 0.53 seconds during a short measurement period.

The site response was estimated as it follows: natural frequency (fo) and amplification factor (Ao) of the soil by means of the spectral quotient (H / V, H = horizontal, V = vertical) with environmental noise records.

The data was processed with the GEOPSY program (free SESAME program). A record of 6 minutes duration (360 s.) divided into time windows of 25 s (Iw) without overlap.

The windows with transient signal were eliminated with what was 83% useful record for the analysis. In total, 12 windows (nw) were used. Figure 3 shows the register and the time windows of the three components (Figure 3).

The Fourier spectra (FFT), by window and component, were calculated using damping at the ends of the windows (tapering) and smoothing. The spectrum of the horizontal component (H) is the geometric mean of the N-S and E-O components. From the spectral quotient of each window, the average H / V was obtained. (Figure 4).

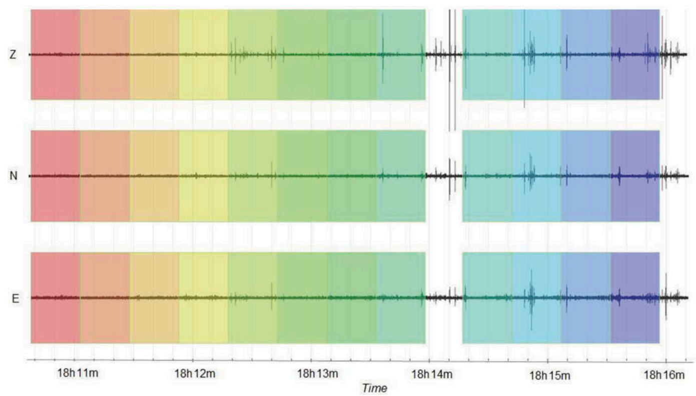

Figure 3. Record of 3-component environmental noise and time windows for H / V analysis.

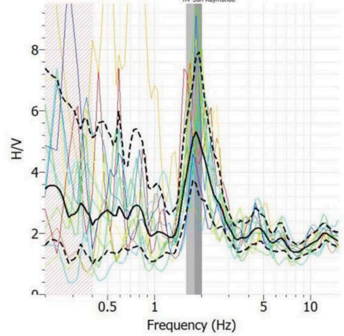

Figure 4. H/V curves by window (in colors), average (continuous black line), deviation of the amplitude (dashed black lines), (fo) and its standard deviation (gray bars).

Table 1. Conditions to determine the reliability of the average H/V curve.

$fo > 10 / I_w = 0.4$ Hz	$n_c = I_w \cdot n_w \cdot fo > 200$	$\sigma_A(f) < 2$, $[0.5fo, fo^-]$ $[fo^+, 2fo]$
yes	yes	Does not apply

Table 2. Conditions to determine the clarity of the maximum (peak) of the average H/V curve.

$A_{H/V}$ $[fo/4, fo^-] < Ao/2$	$A_{H/V}$ $[fo^+, 4fo] < Ao/2$	$Ao > 2$	$fo \pm 5\%$
yes	yes	yes	No ($fo \pm 11\%$)

The results were analyzed according to the SESAME criteria (2003: Site effects assessment using ambient excitations). These include 1) stability of the maximum spectral or peak, 2) reliability of the H / V curve, 3) clarity of the peak, and 4) confirmation or correlation with the geology of the site. Being a record, only the last three criteria were verified. Figure 4 shows the H / V curves of the windows and the respective average curve with errors or deviations in frequency (fo) and for amplification factor, A (f).

The average H / V curve has a peak at p = 1.9 ± 0.23 (to ≈ 0.5 s) with an amplification factor, Ao = 5.1 ± 2.7. The reliability criteria of the H / V curve (Table 1), where nc= number of cycles and σA (f) = standard deviation of the amplitude.

For the clarity of the peak, the average curve H / V meets three of the four conditions according to Table 2, in which AH / V is the amplitude of the curve in the indicated frequency range.

Although these results correspond to a single record of short duration, it meets most of the criteria indicated as to the correlation with the geology of the San Raymundo site. The results presented here should be considered preliminary. To verify them, it is necessary to increase the number of measurement sites (at least 4), the time of recording (at different times) and to vary the measurement time (during hours of less traffic of people and vehicles).

7 RESULTS

7.1 *Soil study*

For this study soil tests were carried out at two different points in order to establish the quality, behavior and oscillation effects of the seismic wave of the soil, based on its physical properties.

The samples were obtained 150 meters from the infrastructure of the church of San Raymundo, as it is a fully urbanized area. Drilling of wells excavated within the national patrimony is not allowed, it was carried out in a nearby land of natural soil.

The studies carried out in the Soil Laboratory (in3) were the following: granulometry, Atterberg limits, sand equivalent, natural humidity, and classification by SUCS and AASHTO.

At the same time, mechanical tests of the soil of pit one were carried out because it was considered critical based on the results of the physical properties, taking into consideration the following analyzes: determination of the angle of internal friction, cohesion, wetness and dryness unit mass. The granulometry in sample 1, values were obtained in which passes 99.85% the sieve number 10 (2.0 mm), 93.88% the number 40 (0.42) and finally 71.69% the number 200 in being shown that it contains enough fines to create plasticity in the soil, is defined as sandy clay soil with 71.69% clay and 28.31% sandy soil. While the sample 2, present characteristic of soils where predominantly low plasticity silts presenting in 57.30% for silty soil, sands in 42.56% and gravel in 0.13%. Because of the plasticity values obtained in the limits of Atterberg it is necessary to take precautions of moisture filtrations by rain or by phreatic level.

According to the results obtained from the tests of the sample number one is interpreted as material with plasticity (IP) of 20.43% based on results of the liquid limit of 41.50% and plastic limit of 21.07%, resulting in a material with a tendency to present settlements. This is due to the relatively high value of the liquid limit in the presence of humidity due to saturation. Sample number two presents plasticity (IP) of 8.95% based on tests of liquid limit of 28.25% and plastic limit of 19.30% that in the same way that sample one has a certain probability of having settlements, but in smaller proportion.

Soil samples at depth 1.15 meters contain 34.53% moisture for sample number one and 16.78% for sample number two. The purpose of establishing the natural humidity of the soil is to verify the plasticity relation with the data obtained from the Atterberg limits tests and in the same way, to relate them with the parameters of resistance to soil cutting. According to the results obtained from the tests, it follows that sample number one will be the critical to consider in the seismic development of a certain structure.

The sand equivalent test for sample one is 1.80% and sample number two is 2.78%. Both results obtained show low sand content which determines that the quality of the soil under study are clays and silts respectively with a certain degree of plasticity. The sand equivalent is a test that is complemented by the Atterberg limit test.

According to the SUCS classification, samples 1 and 2 are classified as; (CL) inorganic clays of low to medium plasticity, clays with gravel, sandy clays, silty clays, poor clays. The description (OL) is organic silt and organic silty clays with low plasticity. For the AASHTO classification, sample 1 is classified as A-7–6 (12) mainly clay soils and sample 2 as A-4 (4) mainly silty soils. As part of the laboratory tests, the results of the cutting test, wet unit weight, internal friction angle and soil cohesion are shown in Table 3.

The results obtained in the analysis of the direct cut test shown in Figure 6 can determine that the studied soils have low friction capacity due to their proximity within natural humidity of the soil and the liquid limit, causing weakness in the soil support value.

Based on the results of the physical properties, it is concluded that the predominant soils found are plastic silts and clays with low percentage of sands as identified in the granulometric data. From the classifications by SUCS and AASHTO, both classifications indicate that soils are susceptible to being affected by settlement processes in the presence of humidity. The presence of high quantity of soils with plasticity predisposes the study area to seismic waves extension with effects of increased oscillations on the structures. Corresponding precautions must be taken in the foundations of the structures of certain height since at higher height, greater oscillation.

Table 3. Mechanical properties of soil in sample 1. Inorganic clays of low medium plasticity and sample measurements: 2.5x1.0”.

Test Specimen	Normal Stress (kg/cm^2)	Shear Stresses (kg/cm^2)	Area (cm^2)	Height (cm)	Unit weight moisture (T/m^3)	moisture %
1	0.32	0.575	31.67	2.54	1.756	30.35
2	0.63	0.734	31.67	2.54	1.704	32.13
3	1.26	1.119	31.67	2.54	1.768	30.07
4	2.53	1.241	31.67	2.54	1.704	34.15

*Strength parameters: Angle of internal friction Ø=16.52 grades. Soil cohesion C= 5.66 Ton/m^2

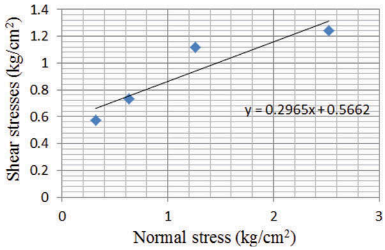

Figure 6. Graph of internal friction angle and soil cohesion (Sample No. 1).

Table 4. Results of compressive strength of adobe

Specimen identification	weight (kg)	specific weight (kg/m^3)	% Moisture	failure load (kgf)	net area (cm^2)	Strength (psi)	Strength (kg/cm^2)
Sample 04	2.52	1578	3.73	3447.34	170.46	287.6	20.22
Sample 05	2.63	1622	3.84	3265.9	175.79	264.2	18.58
Sample 06	2.62	1588	4.71	3084.46	167.6	261.8	18.4

Table 5. Results of bending resistance in adobe

Specimen identification	weight (kg)	specific weight (kg/m^3)	Load L/2 (kg)	Inercia (cm^4)	Strength (psi)	Strength (kg/cm^2)
Sample 04	3.06	1569	27.9	134.185	64.1	4.51
Sample 05	3.05	1588	26.7	130.142	62.4	4.38
Sample 06	3.14	1579	32.6	141.233	72.2	5.08

7.2 *Properties of adobe*

For the adobe material used for the elaboration of the experimental model, tests of specific weight, humidity, granulometric analysis, compressive stresses and flexural strength were carried out. Laboratory results show compressive stresses between 18.40 kg/cm^2 and 20.22 kg/cm^2 of fresh adobe blocks. These values are within the resistance range for this type of material. According to Meli (1998), the resistance for the adobe is between 5–20 kg/cm^2. This resistance is with the addition of straw or some organic material that decreases the contraction of the material and increases its resistance. The modulus of elasticity was not determined in this study, but the value used for calculations was 3,000 kg/cm^2 based on Meli (1998).

7.3 *Seismic signal*

The church suffered significant damage in the earthquake of February 4, 1976, whose event had a magnitude of 7.5 degrees, currently does not have this seismic record. In order to replicate the mechanism of failure of the structure, the earthquake of November 7, 2012 was selected, which is one of the most recent and significant seismic events that occurred in Guatemala, which caused damage to the cultural heritage and has a magnitude similar to the earthquake of 1976.

The earthquake of November 7, 2012 gave place to the subduction zone between the Cocos plate and the Caribbean plate, whose epicenter is located on the Pacific coast, latitude 13° 59’ 13” N and longitude 91° 57’ 54” W and its magnitude was 7.4 Mw (USGS, 2012). This event was sensitive to Guatemala, El Salvador, and part of Mexico. It was registered at the Seismological Service station (in3) in Guatemala City, located 188 kilometers from the epicenter.

In the recorded signals, a maximum acceleration of 19,995 cm/s^2 is observed in the NS direction, 20,246 cm/s^2 in the WE direction and 10,631 cm/s^2 in the UP. (Figure 6).

The records were scaled to the design spectrum established by the Guatemalan standard, taking into account specific parameters of the locality and the characteristics of the structure.

7.4 *Mathematical model*

A mathematical model of the Church was carried out at scale 1/8.75 in the software SAP 2000 v.15 to obtain the dynamic properties of structures, displacement and acceleration at specific point of the model. To carry out the linear analysis, the finite element method with a mesh of 1,169 elements was used, assigning to the materials the properties obtained from the

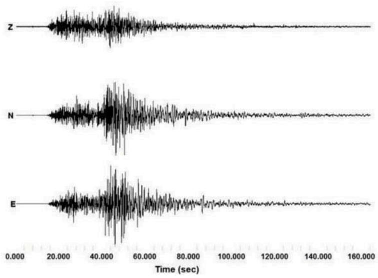

Figure 6. Strong Motion acceleration (SMA). Recorded at the Seismological Service (in3).

laboratory tests and estimating the behavior of the model subject to the seismic action of the scaled event.

The wall elements were assigned properties of Shell Thick, to the vault and dome were assigned properties of Shell Thin. As a result of the modal analysis we obtained the fundamental period is T1 = 0.17 s. The other vibration modes have periods of 0.16 s, 0.12 s and 0.11 s

7.5 *Scale model*

The model of the Church of San Raymundo was elaborated on a geometric scale of 1: 8.75. The criterion used for this scale was that it did not exceed the size and capacity of the vibrating table being adjusted to the following dimensions 2.6 x 3.0 x 1.7 meter. The walls are 0.10 m thick and 0.05 m thick in vault and dome. 750 blocks of fresh adobe of different dimensions were used resulting in a weight of 3.2 tons (Figure 7). The material came from the region of Tecpán, Chimaltenango, where it is still used to produce adobe. The model was constructed to evaluate the behavior of the material and the elastic properties representative of the behavior of the structure.

The model was instrumented with 8 accelerometers ES-U, (1.25mv / g), with 4 G response range and sampling frequency of 100 samples / sec. Three displacement sensors OMEGA 0-10 V LDVT were connected to the MTS controller, as well as a Triaxial Sensor FBA-ES-T validation on the shacking table.

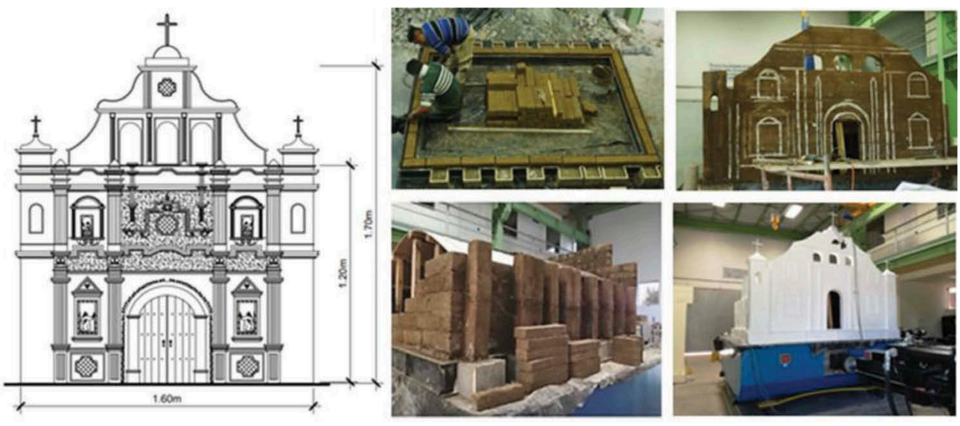

Figure 7. Constructive process of the scale model.

Table 6. Acceleration and displacement results.

		Mathematical model (Scale)				Experimental model (Shaking table)			
		Acceleration (m/s^2)		Displacement (m)		Acceleration (m/s^2)		Displacement (m)	
Earthquake		x	y	x	y	x	y	x	y
x	Wall	2.248	0.353	0.001	0.00005	1.67	0.23	0.00073	0.000043
	Vault	3.14	0.26	0.0004	0.00067	2.76	0.17	0.00035	0.00057
	Facade	1.39	1.981	0.0002	0.0019	1.23	0.589	0.00018	0.00169
y	Wall	0.822	0.29	0.0009	0.00005	0.702	0.23	0.00076	0.00004
	Vault	0.94	0.88	0.0001	0.00083	0.792	0.748	0.00011	0.00058
	Facade	0.41	6.39	6E-05	0.003	0.294	4.608	0.000043	0.0024

7.6 *Comparison of results of the mathematical model vs. experimental model*

To determine the parameters of acceleration and displacement, the same seismic signal was induced to the experimental model and to the mathematical model through a linear analysis of time history. These response parameters were measured in walls, vault and front façade. The maximum acceleration in the vault was measured when the earthquake acts in the X direction. The comparison between both models is shown in Table 6.

As part of the results analysis, the efforts to which the masonry works were determined. The maximum efforts that were observed when the earthquake acts in direction X appear in the vault 0.96 kg / cm2. When the earthquake acts in direction Y, the maximum forces are presented in the façade and are 2.25 kg / cm2. The efforts are shown in Figure 8.

7.7 *Damage observed in model after simulation in shacking table*

The seismic signal was introduced in the longitudinal direction of the structure, observing damages in the facade since this wall has a tendency to overturn due to its heavy element and greater height which provide inertial forces during the event. Then the model was submitted to the earthquake in a direction perpendicular to the facade, producing flexural cracks in the upper part of the structural element (Figure 15). The rear wall was damaged due to the thrust in the

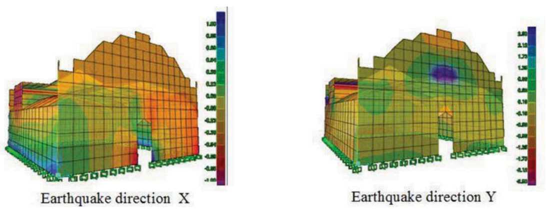

Figure 8. Efforts resulting from the seismic action, in the X direction (left) and Y direction (right).

Figure 9. Damage to the Church of San Raymundo

longitudinal direction due to the fact that it has no restriction against the displacement in a direction perpendicular to its plane because there is no element that provides rigidity to the wall.

8 CONCLUSIONS

The urban area of San Raymundo, Guatemala, is an area of seismic conduction and amplification due to the intercalation of the different geological strata, especially the superficial part of filling alluvium with diverse grain and in some strata with little integration and adherence.

The mathematical model was validated with the experimental model and presented as a result that the frequencies of vibration coincide with the frequencies that were necessary to induce in the experimental model so that this began to present failure. In the mathematical model, it has a fault with the fundamental frequency of 5.86 Hz while the experimental model needed 6.0 Hz.

The experimental model simulated the earthquake (San Marcos 2012, Magnitude 7.4) and showed damages similar to those presented in the Church of San Raymundo in the earthquake of 1976 (Magnitude 7.5). Among these damages, failures due to diagonal tension, fissures due to bending, failure of the façade due to bending and total collapse of the dome and vault are highlighted. This experiment will continue with new models focused on the vault and dome, applying representative loads.

The results of the dominant period correspond to a single record of short duration. This meets most of the criteria indicated. As to the correlation with the geology of the place, the results presented should be considered as preliminary. To verify them, it is necessary in the near future to increase the number of measurement sites (at least 4), increase the time of recording, and vary the measurement time (during hours of less traffic of people and vehicles).

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