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Structural Analysis of the Bell Tower of the Basilica De La Merced of Lima

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Abstract The Bell Tower of the Basilica de la Merced de Lima is a monument with its own personality in itself, was built by master masonry Alonso de Morales as contract signed May 12, 1589 whose original is in the General File Nation of Peru. Until now has been repaired several times due to damage to large earthquakes that destroyed the city of Lima in more than one occasion.

The Bell Tower of the Basilica de la Merced de Lima is the construction of unreinforced brick masonry higher and that has continued for over four centuries in the same location and is without doubt one of the famous monuments of the city of Lima.

For structural analysis, the monument was modeled and analyzed by finite element method, models were developed to adjust and show impressive results and consistent with the records of damage were made in the year 2005 date when the monument was established structurally.

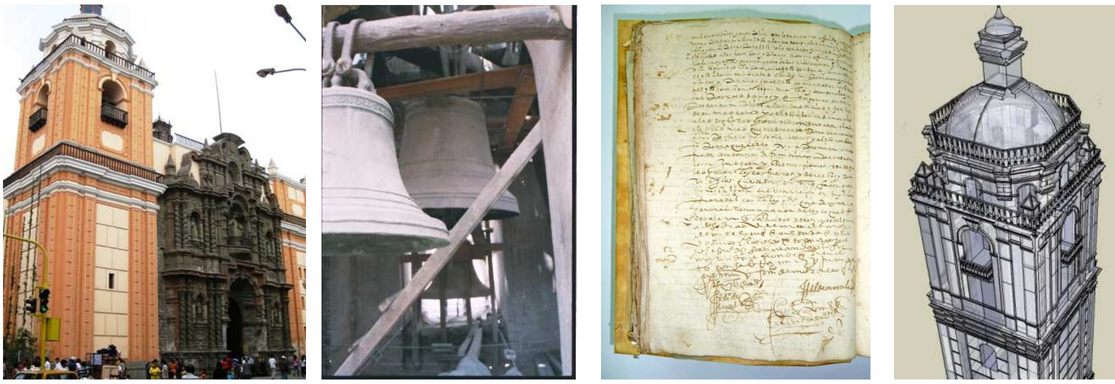
An important historical record supports the technical scope of the investigation. Interesting comments on its formidable seismic capacity, and their significant contributions in knowledge of construction techniques of the builders of the sixteenth century in Lima, reveal a building that surprises with its apparent simplicity but it saves a lot of knowledge about engineering techniques applied to the great monuments that have survived from the years in which Lima was the largest metropolis in South America.

Keywords: Structural, finite element, conservation, monument, tower

Introduction

The Basilica de la Merced is located at the intersection of Jiron de la Union and Miro Quesada Street in the Historical Center of Lima. The beginning of the construction of the Basilica dates of the year 1535 and the Tower of the year 1589, according to the employment contract existing in the Archivo General Office celebrated between the authorities of the Order de la Merced and the builder Alonso Morales signed the contract May 12, 1589, by the Order de la Merced signed Fray Diego de Angulo, there certified by the Notary Rodrigo Gómez de Baeza (Archivo General Siglo XVI), at the moment the Tower maintains the characteristics that are mentioned in the contract and possibly most of it is original building.

About the year 1759 the Tower was repaired, probably affected by the Earthquake of year 1746 (Silgado 1978), where it details to works of lime and brick, work of wood, cost of bells, raising them and putting this work perfect. The 20 of November of the year a 1790 new seismic movement affects the Tower, causing the fall of two bells affecting to the church (Barriga 1944). The 2 of Julio of the 1860, architect Guillermo D'Coudrey conducts an inspection and do an analysis of the state of the Tower, demonstrating that it is necessary to knock down her for considering that the repairs would be so costly as a new work, it should be mentioned that apparently the architect was referring to the poor condition of the tower be found by those years and whose damage apparently remained until the twentieth century.



(a) (b) (c) d)

Figure 1: (a) Front View of the Tower, (b) Internal view of the bell Tower, (c) Employment contract existing , (d) Isometric view

Structural Features

The structure is composed of masonry walls of two meters of thickness, masonry units are solid, of handcrafted manufacturing and approximate measures 9x14x30 cm, the mortar was made with lime and sand, meetings in average measure 2.0 cm. The Tower measures eight meters of side and is of square plant, the total height from street level to the top of the dome is 35.00 meters. The walls form a rigid prism and they lift throughout the same without variations safe by small vain openings type and the presence of pillars that finish off in four means arcs point which they as well support the “drum” that serves as support to the dome of light material that crowns the tower. This dome was constructed with wood segments and the membrane of the originally domo was formed by based clay blocks as they exist in the other dome of the Basilica.

Structural Conditions

The structure presented cracking in the walls, in the bases of the pillars, in the arches, and between vain to everything long of your development, we must consider that has been repaired in several occasions and has supported at least fifteen earthquakes of high magnitude.

Figure 2: Views of structural damage of the year 2005

Geotechnical and Seismic Considerations

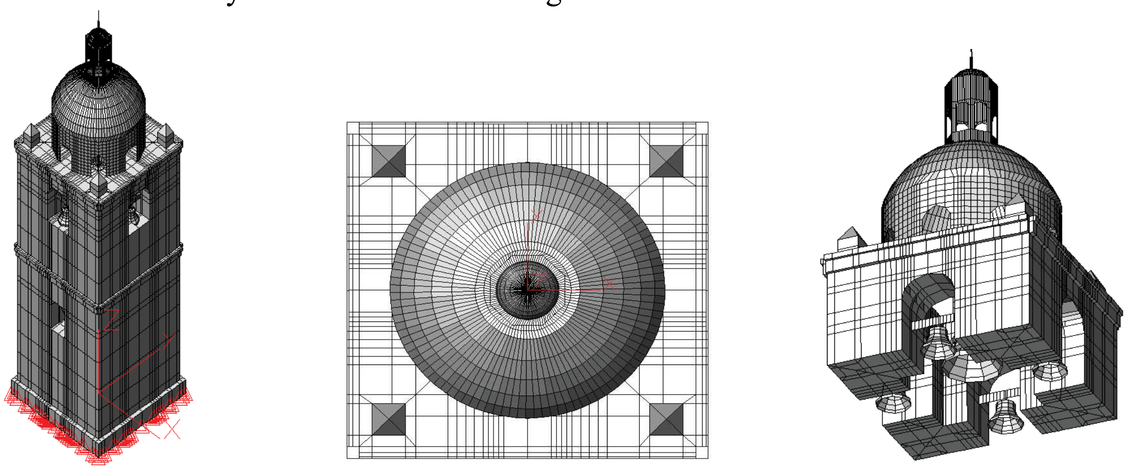
The soil foundation of the Tower structure is a zone conformed by the conglomerate of the debris cone of the Rímac river with layers that arrive at the 200 meters of thickness (Martinez, 2007). This zone presents excellent conditions and geotechnical characteristics for the superficial foundations. According to the seismic microzoning of Lima City, the Tower of Basilica de la Merced is located in ZONE I, on an alluvial gravel layer. This alluvial ground layer has a rigid behavior, with periods of natural vibration between 0,1 and 0,3 seconds. The seismic amplification factor by local effect of the ground in this zone is S = 1,0 and the natural period of the ground Tp= is 0,4 seconds, corresponding to a ground type 1 of the E-030 Peruvian Norm of earthquake.

Mechanical Properties of Materials

The walls that form the Tower are composed by units of bricks of clay joined by mortar of lime, for the present study there took the properties of the material found in other similar studies (Proaño et al, 2007) and whose results we adopt to give major accuracy to our analyses, these are: density of 1.7 gr/cm3, compression strengthen of 2.2 MPa (22 kg/cm2) and module of Elasticity of 1,110 Mpa.

Structural Model

The models of the Tower were developed for the analysis by the Finite Element Method. In the modeling have been used 6292 polyhedral elements type `"brick" in walls, pillars and arcs as well as type `"plate" or planes with continuous thickness, of quadrangular and triangular form used to model dome, structures of wood, walls, etc. They form 11930 nodes. In the models there have been included the bells and the wood bearing , however, that these elements and the effects they may have in the structure have not been taken into account in this work. The building elements that have not been modeled are moldings and other elements of decorative character since they do not have major structural importance. Analysis has been considered linear elastic to predict the stress and displacements, the walls materials, the brick and the mortar of lime, have been considered a homogenous and isotropic behavior within the elastic linear range and the fixed foundation, nevertheless it must consider that these hypothesis don't exact and future research must consider the behavior nonlinear of the material. The adjust of model accuracy is verified with the coincidence between the Tower analysis results and the damage records found.



(a) (b) (c)

Figure 3: a) Global model of the Tower, b) Plan view of model, c) Isometric view

Structural Analysis Results

Analysis of the building considered the elastic behavior, considering the dead loads and those of earthquake, the live load and wind load have not been taken into account. The seismic analysis will inform to us on the vulnerable zones in the construction and to identify the found damages. Has used a pseudo accelerations spectrum according to the Peruvian Seismic Standard, the following parameters: Factor of Zone (Z=0.4), Factor of use (U=1.5), seismic Amplification factor, (C=2.5, Tp/T< 2.5), Elastic Reduction factor (R=1).

Lateral displacement at the level of the dome was caused by the shifting of the 8 pillars, have been previously collapsed due to low capacity to shear stresses, it would explain the presence of pieces of wood embedded in the pillars, which would give better performance and flexibility. However, effects of the earthquake produce shear stresses on the order of 1.3MPa (13 kg/cm2).

Even for low-intensity earthquakes, the limited capabilities of the pillars is easily exceeded, which agrees with the observed damage.

The analysis results show maximum lateral displacements of 15 cm in the dome area at 9 cm from the wall. They are related to insufficient lateral stiffness at the pillars and the dome, which was probably made of brick and collapsed to be rebuilt several times.

The tower has a fundamental vibration period of 0.36 seconds, is very rigid. The vibration modes were primarily the lateral and torsion were fewer in number. The masonry building has good capacity for shear stresses resistant and is below the allowable capacity. However, stresses originated in the key of the arches, with values exceeding 0.1MPa (1 kg/cm2), exceed the capacity of unreinforced masonry.

The pillars and dome at the top of the tower are very flexible compared to the rest of the structure because of its mass and height. When they are analyzed as separate structures, these pillars have a fundamental period major than the 0.36 s obtained for the entire building. The dome originally built with masonry units to collapsed due to the stress traction at the support area, these being 0.4 kg/cm2 very low but sufficient to cause collapse even by dead loads, this structural failures are common in the domes.

We can say that the weight of the structure has an important role in preventing the total collapse of the building, despite the cracks in critical areas and the key pillars of the arches, and cracks along the east and west walls, the structure is held together. We believe that through the cracks the tower it obtained other level of ductility, through these can dissipate the earthquake energy. This hypothesis could have been the reason so that the structure has not arrived at irreversible levels of collapse.

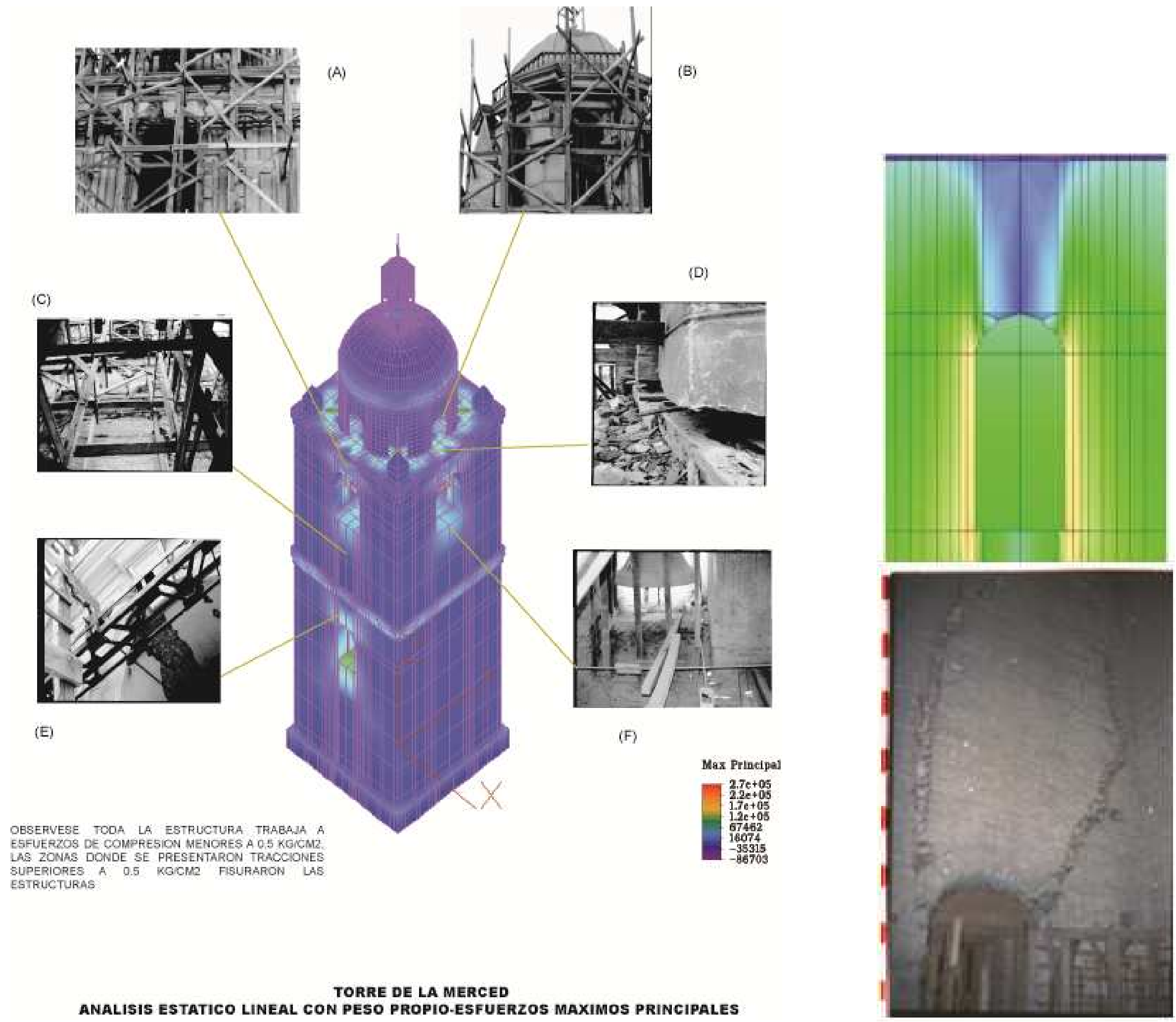
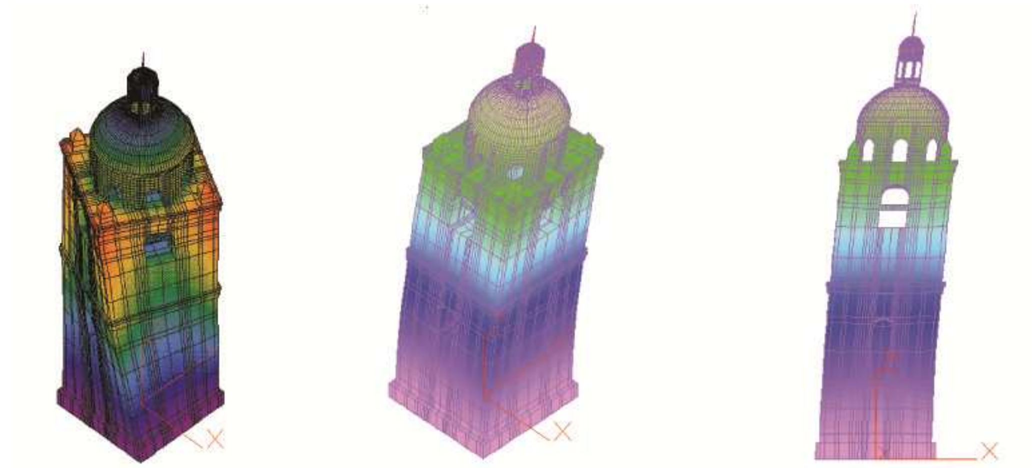


Figure 4: Shear stresses concentration and damage agreement



(a) *(b)*

Figure 5: (a) Vibration Mode: 3th mode, T= 0.2 s (b) Deformed shape for modal superposition, maximum displacement: 0.15 meters

Conclusions

The weight of the walls of the Tower of the Basilica de la Merced was the important factor in order that it has resisted the values of shear force for earthquake without coming to the total collapse. The analysis of walls needs to do a more accurate calculation of the seismic reduction factor R, taking into account the energy dissipations product of the progressive crackings in the structure.

It's possible the presence of structural resonance effects due to close in the values of periods of soil and the Tower, plus the damage is quite consistent with the maximum stresses for dead loads, to be deepened in this statement.

The relative high weight of the structure has an important role in preventing the total collapse of the building, for this reason the structure is held together in spite to the cracking. After the cracking tower it obtained other different level of ductility and change of vibration period, through these cracks can dissipate the earthquake energy. Researches are necessary to give satisfactory answers.

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