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SEISMIC VULNERABILITY OF CUZCO CATHEDRAL, PERU

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SUMMARY

The building of Cuzco Cathedral was built on 1560, over a part of Inca's Wiracocha palace. The structural system of the building is compose of stone masonry walls and columns and compose domes. The building was severe damage by 1650,1707, 1950, 1986 and 1991 quakes. There have been at least five retrofitting processes on the structure showing that how vulnerable are the domes, arches and columns. Due to cracking on down part on columns, the seismic vulnerability of Cuzco Cathedral was study.

In order to produce a diagnosis of the seismic behavior of this building, three Finite Element Numerical models were developed: a column model, column-arch-dome model and the whole structure model. The analytical model was developed using the results of a series of material test of the stone on columns, arch and dome material. Due to the action of the flexibility of domes, the modal shapes on the whole structure model were used as calibration parameter for the model through the Microtremor measurements (period of 1.15 sec on domes and 0.23 sec. on columns). Numerical simulation of the Cuzco cathedral with quakes of PGA 600 gals and PGA 1200 gals were performed, with a maximum response of 28 mm. on the top of the towers and 8 mm. on the top of the domes; this displacements could be consider small for the structure, however high tension stresses (8 MPa) were produced on the domes. It could produce brittle failure on the domes. If domes fail the columns became isolated structures, then the isolated structure behave similar to the column, arch, dome model with shear stress of 6.5 MPa and normal stress of 28 MPa, where this values are quite excessive for the used material. Then failure pattern is predicted as failure in domes following with arch and columns failure.

INTRODUCTION

Cuzco Chedral is located in the main plaza of Cuzco the former capital of Peru in Inka's times. The cathedral starts the construction in 1560 over a part of Inca's Wiracocha palace. Since that days the Cathedral was demanded by several strong quakes. The quake of March 31th 1650 its structure suffers severe damage with the collapse of 17 archs without domes and the collapse of one dome in the main altair. An strong quake on May 21st 1950 demage the towers, main entrance of the cathedral and some domes. In 1951 the retroffiting works started under the support of the Spanish Goverment and finished in 1953. The April 5th 1986 damage some domes and the towers of the church. The towers has a retroffiting jobs between 1987

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to 1989. Finally with July 9th 1991 damage on bells supprot structure produce the closerure of this area till 1995 where under the support of the German Goverment the structure was retrofited.

ABOUT THE STRUCTURE

The Cuzco Catherdal has three buildings: the main church, the Triunph church and Sacred Family church. Both churches are located at each side of the main church as is presented in Figure 1.

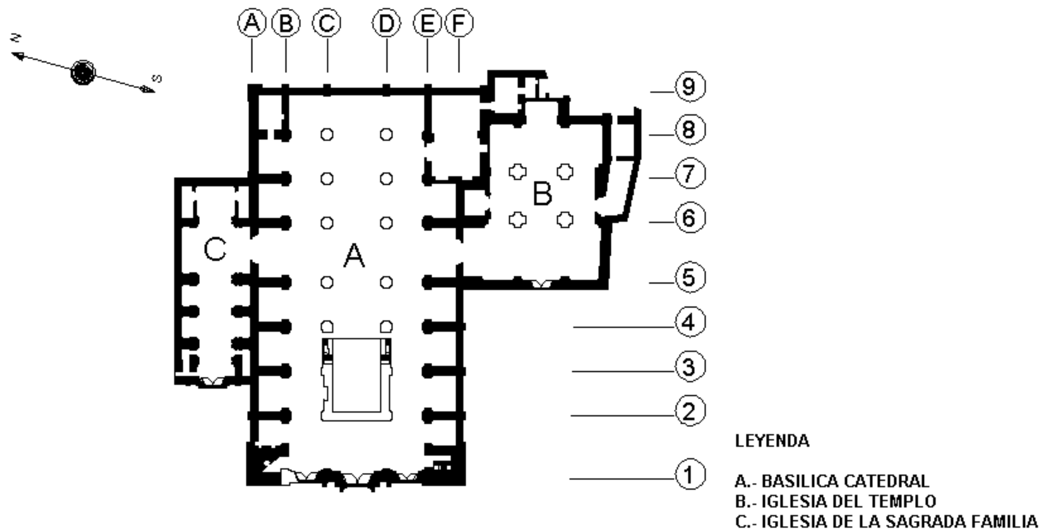

Figure 1: Overvie of the Cathedral

The main church is a contruction with characteristic Sapanish style. Its plant described a rectangule of 86m x 46 m. In the midle of the church there are two huge doors to comunicate the main church with the other two temples. The three buildings are limited by 14 big columns. This church presents elements that have been repetaed by other churches in Southern Peru. The structure is high stiff due to the section of its walls. The thickness of walls is variable, between 1.60 m. for indoor walls to 2.00 m. for outside walls.

CHARACTERISTICS OF THE MATERIALS

The predominat material is the stone. The visible faces of the stone masonry have quite regular configuration and good finishing. There are some areas where had not compromise with the structural support with less important demand of streses it was use a conglomerade of stone in morter matrix with out any finishing. This last configuartion is less resistance than the regular visible walls. The archs and domes hay diverse materilas and ther are evidence of reconstruction and looks like part of them has been replaced.

In order to quantify the resistance and stiffness of the stone five compression test on cilinders of 5 cm. and 9 cm. diameter has been performed. Two of the samples were taken directly from the upper part of the column and the othres were extracted by the chuch incharge.

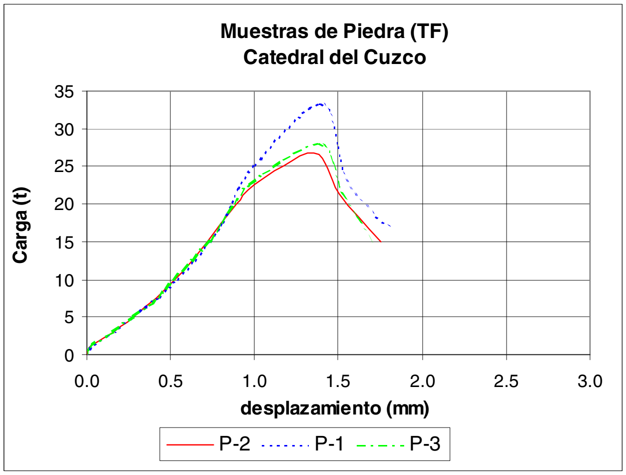

Figura 2. Stone sample results

Figure 2 shows the force deformation relation obtained from the samples. The way of the compresion failure is typically in tension in the transversal direction. After apply low level of stresses (30% and 50% of its resistance) we observed the first cracks in longitudinal direction. They will propagate and appear un the axial direction and finally opened because transversal tension producing a pattern like the observed in Figure 3.

Figure 3: Faillure on stone sample.

Using a regresion process of the curve presented in Figure 2, it was found the acerage resistance value for the samples 451 kg/cm^2 (45 MPa) and a Moulus of Elasticity of 194000 kg/cm^2 (19400 MPa). The density of this stone is in the order of 2.2 g/cm^3.

The columns of the Cathedral have a box section of stone masonry filled with a mix mortar. For the filled material a densty of 1.76 g/cm^3 was found. Axial compresion test with the results of are presented in Figura 4. The compresion resistance was 10.9 kg/cm^2 (1.09 MPa). Under a regresion process in the elastic range a Modulus of Elasticity for the filled material of 6270 kg/cm^2 (627 MPa) was found.

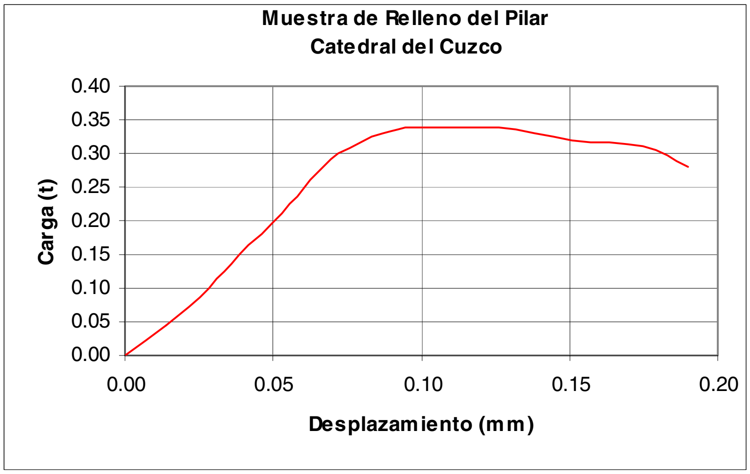

Figura 4: Compression test on Filled material in columns.

Also test of the filled material for domes were performed. Here the density of this materila was in the order of 1.76 g/cm^3. After a series of compresion test as the presented in Figure 5, the average value of the compresion resistance for the samples of 5.8 kg/cm^2 (0.58 MPa) was found. After a regression process in the elastic range, a modulus of elasticity of 3480 kg/cm^2 (348 MPa) is found. Finally and after a comparison process with analogous problems it is possible to consider a tension resistance of 1/10 of the compresion resistance.

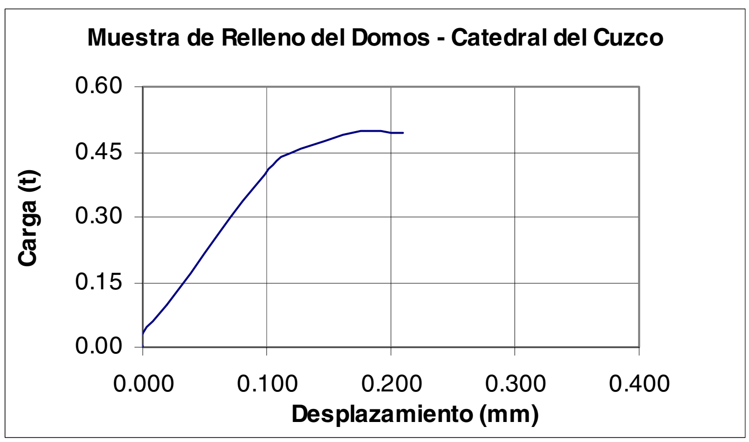

Figura 5: Compresion test in filled material in domes

STATE OF THE STRUCTURE

The main damage presented in the structure appears in the columns. In Figure 6 it is possible to see the vertical cracking in the stones. Also it is possible to observ the damage on the borders of the stones. In the right habd side picture is possible to observe the horizontal shift of the blocks which represents an unlinegment on the border and surfaces of the stones.

Figure 6: Damage on stones on columns

Figure 7 shows the state of the down part of the column. Here is obvious the vertical opening between stone blocks. Figure 8 shows the cracks in the stone in vertical pattern. It could be attributted to excesive stress on the section or a possible interaction from the upper part of the structure coming from domes and arch reactions over the column.

Figure 7: Opening on column base

Figure 8: Vertical cracking

MICROTREMOR MEASUREMENTS

Due to the action of the flexibility of domes, the modal shapes on the whole structure model were used as calibration parameter for the model through the Microtremor measurements. For that purpose microtremor measurements were performed over the domes and over the columns. Also the soil dynamic characteristics was measured soil type classification purpose. In the case of the soil measurements the horizontal and vertical movements presents a peak in the Fourier Spectra of 1,26 Hertz (Figure 9). It means the period of the soil in its surface layer is in the order of 0.8 sec. which is typical of a flexible soil. However the structure has a foundation very deppely. When measures on columns were performed it was found an average value on X direction at 4,3 Hertz (Figura 10). It will correspond to a natural period of 0,23 s. Finally when domes frecuencies were measured a peak amplitude was observed at a frecuency in the order of 0,84 Hertz. It correponds to a period of 1,17 sec. This values apperas also for horizontal components If this values are compared with the values measured over the columns is possible to conclude arch and domes are more flexible than columns. Under this flexible conditions the following consecuences are possible:

- Large displacements in domes are possible and it could produce openning bewteen blocks and the collapse.
- The performance of the combination domes and arch as a diaphragm is not corrected al all for the numerical analysis.

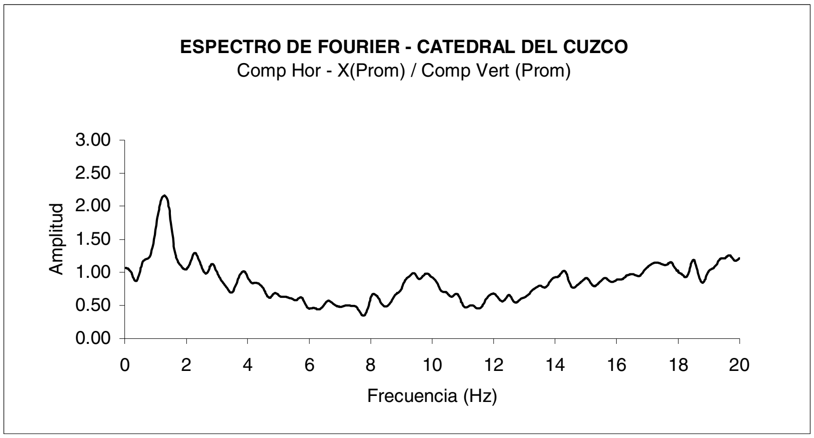

Figure 9

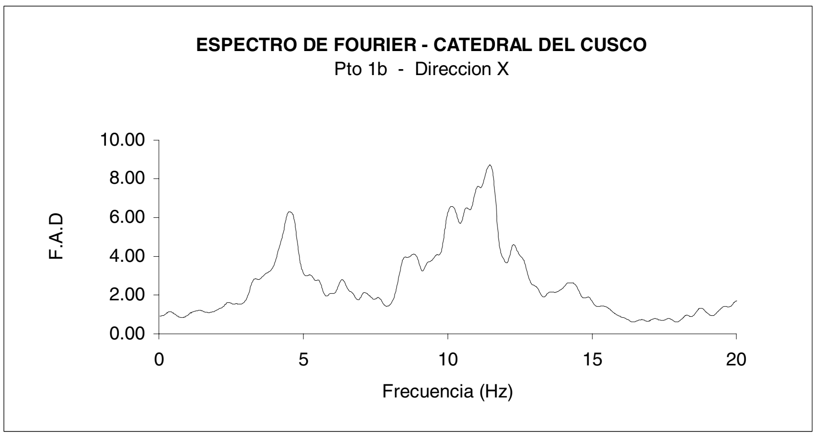

Figure 10

NUMERICAL SIMULATIONS

For the numerical simulations, three finite elements models were considered: a central column alone, the central column plus the arch and domes, and global model of the whole structure. The purpose of the first and second models was to obtain equivalent parameters to be used in the whole model structure. Also the study of performance stress level was complement purpose.

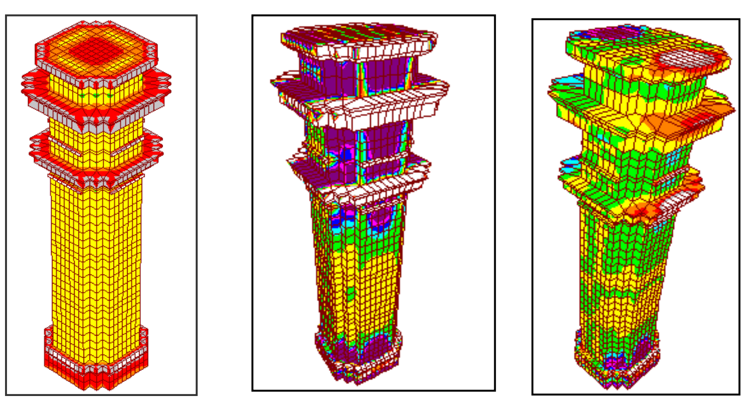

Figure 11: Stresses in column model

In Figure 11 is possible to see in the left figure the vertical stresses due to gravity load, where a stress conscentration because the load of domes and arch is supported by the external ring of the column compose by stone blocks. The central figure shows horizontal stresses due to permanent load. Its explain why the stones separated from each other because the filled mortar can not take this level of stresses. The right figure presents the vertical stresses due to seismic loads. Here reverse stresses appears in down part of the column and stress concentartion appears.

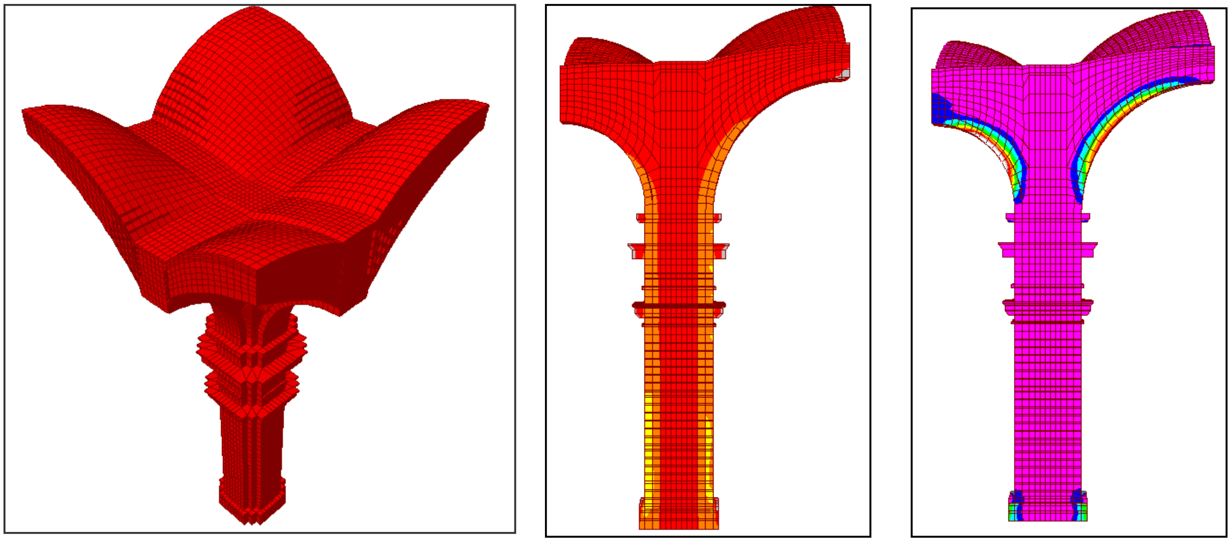

Figure 12: Arch – domes – colum model

Figure 12 presents the model and stress which consider the arch – domes – column interaction. Here the left introduce the finite element model. The central figure presents the vertical streses due to gravity loads. Here the normal in horizontal direction are less tha 0.1 Mpa in columns. In domes and arch the stress level in tension are in the order of 0.1 Mpa and compresion in the order of 0.75 Mpa. The right hand side figure shows the shear stress concentration on arch because seismic loads, the ones are in the order of 6.5 Mpa in the start of the arch. Also in columns the shear stress level reach a value of 3 Mpa. In the face of the columns and 0.5 Mpa in the nucleous.

Figure 13: Cuzco Cathedral

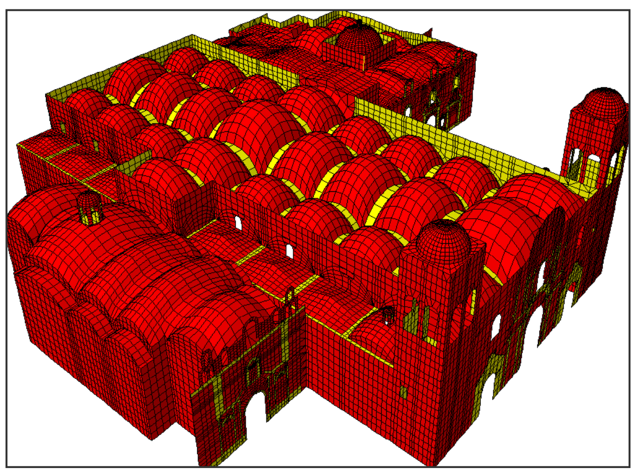

Figure 14: WholeCathedral model

In the whole cathedral model presented in Figure 14, the prior models where used in the generation of equivalent elements which represents the behavior of columns, domes, arch and its interaction.

Numerical simulation of the Cuzco cathedral with quakes of PGA 600 gals and PGA 1200 gals were performed, with a maximum response of 28 mm. on the top of the towers and 8 mm. on the top of the domes; this displacements could be consider small for the structure, however high tension stresses (8 MPa) were produced on the domes. It could produce brittle failure on the domes. If domes fail the columns became isolated structures, then the isolated structure behave similar to the column, arch, dome model with shear stress of 6.5 MPa and normal stress of 28 MPa, where this values are quite excessive for the used material. Then failure pattern is predicted as failure in domes following with arch and columns failure.

CONCLUSIONS

- Cuzco Cathedral is considered one of our National Monuments who has been demanded by many quakes during his life. According with the historical records failure on domes, arch and towers occurs in the pased. One of the likely failure place were the domes in this structure.
- Investigation of material properties was done for column, arch and domes. Here stone of columns presents high resistance for the face of the column. However the filled mortar used in the core of the columns has less resistance than the stone blocks in the border. In general the materials present good performance but there some damage elements becuase the seismic structural configuration.
- The seismic structural configuration of the Cathedral presented in the numerical analysis shown the flexibility of the domes and arch system. Even the existance of external stone shear walls.
- The poor capacity to resist tension stresses of dome elements will produce the collapse of the structure if non retrofiting of the domes is executed. Fortunatly two years before a replacement of damage areas of domes was performed by Cuzco's Church authority.

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