SAHC2014 – 9th International Conference on
Structural Analysis of Historical Constructions
F. Peña & M. Chávez (eds.)
Mexico City, Mexico, 14–17 October 2014

STRUCTURAL EVALUATION OF MASONRY VAULTS

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Keywords: Masonry Vaults, Stresses in Vaults, Finite Element Analysis of Vaults.

Abstract. *Mexico has a valuable architectural and cultural heritage in its historical temples that it is very important to preserve. With this purpose, the objective of this research is to establish a procedure for the structural evaluation of these constructions to assess the stresses, deformations and failure modes that allow us to decide the best strategy to strengthen them. A case of study is presented that consists in the structural evaluation of the ex-temple of Saint Augustine in the city of Zacatecas, Mexico. This building is almost 400 years old; its construction took 4 years and was finished in the year of 1617. Its roof system, made of lunette vaults, presents large deformations and extensive cracks. The finite element method is used to analyze the ex-temple. It is also presented the topographical survey carried out to obtain the actual deformed geometry of the ex-temple. The vaults of the main nave are analyzed considering the wall and buttresses that support them. A structured mesh was generated allowing the use second-order hexahedral elements. These elements provide a very good approximation of the structural response without the need of using a very refined mesh. The topographical survey allowed measuring the deformed configuration of the three vaults that form the main nave. The middle vault is the most deformed with a maximum vertical displacement of 52 cm on a span of 12.0x7.7m It was found that the large deformation were caused by the lateral displacement of the walls and the axial deformation of the arch that support them. The vertical displacement at the keystone of the arches is 19 cm. It is concluded that the lateral displacement of the walls was produced by the horizontal thrust of the vaults and, mainly, by the deformation of the soil under the foundation of the walls. A study of the thrust surface in the vault is performed to observe how this surface changed its trajectory as the wall and arches were deforming.*

1 INTRODUCTION

The historic temples represent the heritage of our native culture. It should be borne in mind that these structures, with the passage of time, have suffered deteriorations, which in some cases are considerable, and in others cases have led some buildings to collapse. Some of the causes that produce this deterioration are: large lateral deformations of the supporting walls and variations in the loads due to modification of the structure and its use. In addition, there was a lack of knowledge of the characteristics of the soil and of a seismic design procedure. These historical buildings were constructed using some geometrical relationships. The study of these structures, made of masonry, has great peculiarities compared to the analysis and design of new structures. The purpose of this research is to use the finite element method to analyze masonry vaults to evaluate their structural behaviour, in order to propose the better strategy for consolidating these structures. It must be borne in mind that we are not working with a homogeneous material or isotropic, which consists of blocks of various sizes laid in various positions. In addition, the lack of knowledge of the characteristics of the materials and the impossibility, in some cases, to test it, make the study of historic structures quite different from that of the conventional ones.

2 DESCRIPTION OF THE CASE OF STUDY

The implementation of the analysis procedure is shown in a case study that evaluates the structural behavior of the former temple of St. Augustine in the city of Zacatecas, Mexico.

The ex-temple of Saint Augustine was built by the religious order of the Augustinian monks, which arrived in the city of Zacatecas toward 1575. This ancient temple represents for the city of Zacatecas one of the most important monuments of its architectural and cultural heritage. Being one of the first monasteries, its construction took 4 years and was finished in the year of 1617; the north facade is shown in Figure 1. The building of 1617 had the roof made of wood, 165 years later the wood roof was replaced by masonry vaults, and in the year of 1782 was devoted and blessed for the second time.

The Saint Augustine ex-temple has had several uses: it was temple, hotel, used for housing and currently is used as art-gallery. During these stages the building suffered different modifications that damaged its walls, the ornamentation in the facades and its structural elements. The aforementioned historical antecedents are explained in detail: 1) the vaults and domes have an age of 232 years counted from the year of 1782 at the conclusion of the construction work of the new temple; 2) apparently to build the new vaulted roof, the original walls were used strengthened with external arcs supported by massive buttresses. Now, the buttresses have ceded due to the thrust of the vaults, this has put the roof system in a situation of risk.

Figure 1: Lateral facade in the north side.

Figure 2: Main facade, its ornaments were removed.

2.1 Architectural description of the ex-temple

The form of the architectural plant is of a Latin cross. The nave measures 12m x 35m and 17m in height. The inside of the transept measures 25m x 8m. The sacristy is located on the western edge of the temple, and measures 20m x 8m. Figure 2 shows the main facade, it is smooth and without ornaments because they were removed when the building was modified to be a hotel. Figure 3 shows the north facade strengthened with massive buttresses. An exterior view of the main dome is shown in Figure 4. The roof of the main nave consists of three lunette vaults with arches, see Figure 5. The main dome and its drum of lights are shown in Figure 6.

Figure 3: Buttresses in the north wall.

Figure 4: Exterior view of the main dome.

Figure 5: Interior view of the vaults and arches of the main nave.

Figure 6: Interior view of the main dome and its drum of lights.

3 RESULTS AND DISCUSSION

A topographical survey of the building was performed to obtain its dimensions in order to prepare a model for the analysis of the building with a finite element program. Figure 7 shows a cross section of the main nave, it can be appreciated in the deformation of the arch and the loss of verticality of the walls.

The main problems of the vault roof are its large vertical deformations and the lateral deformations of its supporting walls. Figure 8 shows a view of the exterior surface of the vaults as compared with the graphical representation obtained from the topographical survey. The graphical representation was evaluated using the MATLAB function **TriScatteredInterp** and plotted using the MATLAB function **surf**.

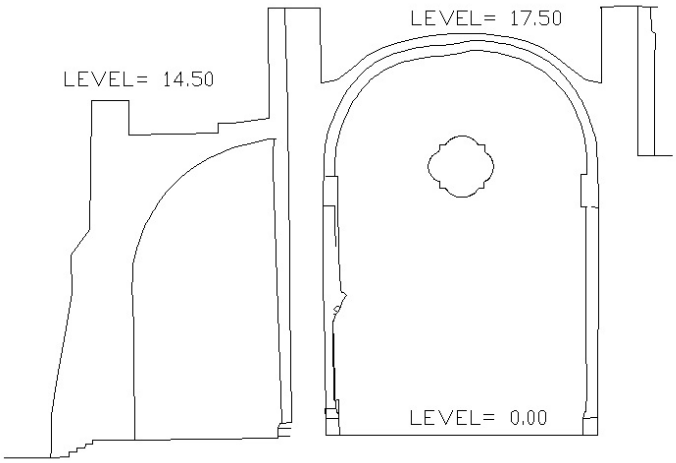

Figure 7: Sectional view of the main nave showing the deformation of arch and the loss of verticality of the walls.

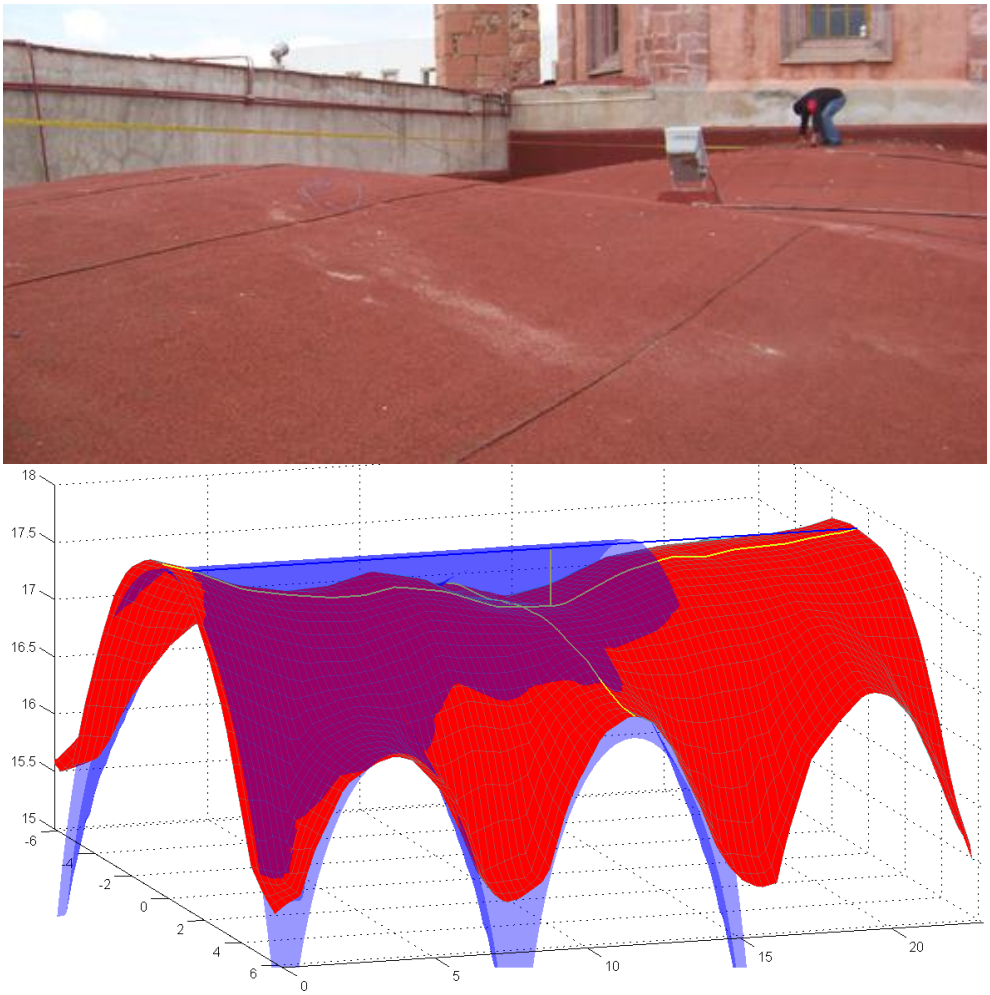

Figure 8: Above) photographic exterior-view of the vaults, below) graphical representation of the vaults obtained from the topographical survey. The deformed vaults are in red and the blue surface represents the assumed original surface when the vaults were builded; the large deformations can be appreciated.

The exterior surface of the deformed vaults is in red; the two yellow lines highlight the larger deformation profile in the longitudinal and transverse directions. The blue surface represents the assumed original surface of the vaults, when vaults were build. The blue horizontal line shows the original profile of the keystone of the vaults.

The topographical survey allowed measuring the large displacements on the three vaults. The central vault is the most deformed with a maximum vertical displacement of 52 *cm* on a span of 12.0 x 7.7 *m*. This can be appreciated in Figure 9 that shows the displacement profile of the keystone of the vaults. The vertical displacement of the keystone of the arches in B and C are 19 and 18 *cm*, respectively.

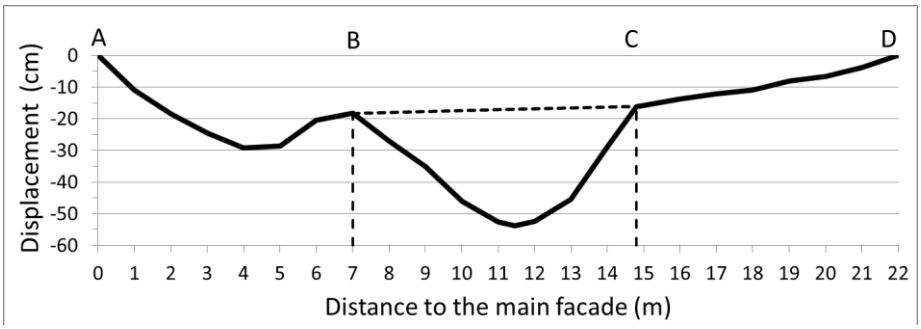

Figure 9: Sectional view of the main nave showing the deformation of arch and the loss of verticality of the walls.

The state of large deformations has induced the formation of extensive cracks on the vaults as it is shown in Figure 10. From this figure it can be seen a large crack in the central vault and the replacement of the bricks in the first vault that had a huge crack in the border with the wall of the main facade.

Figure 10: Exterior view of the vaults when they were repaired on the start of the 1980 decade.

4 STRUCTURAL MODELING OF THE VAULTS

To perform the structural analysis of the vaults, a structured mesh was generated using the software MIDAS-FEA. The mesh was generated by dividing the domain in appropriated subdomains that allow us to use hexahedral elements of 2nd order. Figure 11 shows the structured mesh that models the vaults and arches.

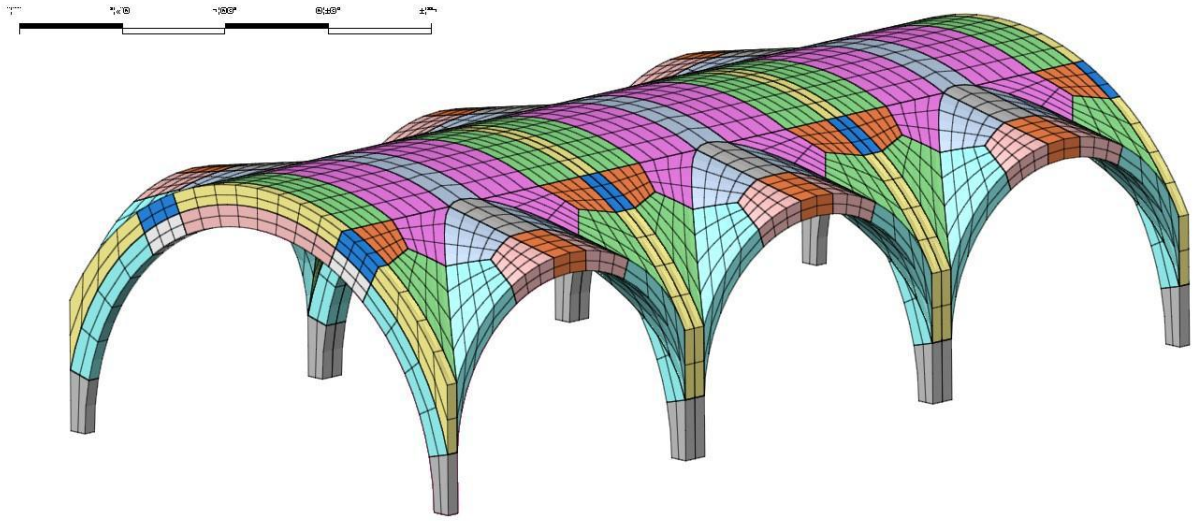

Figure 11: Structured mesh that models the vault and the arches with hexahedral elements.

At the present time of writing this paper the modeling of the building has been concluded, missing only to perform the structural analysis of the model.

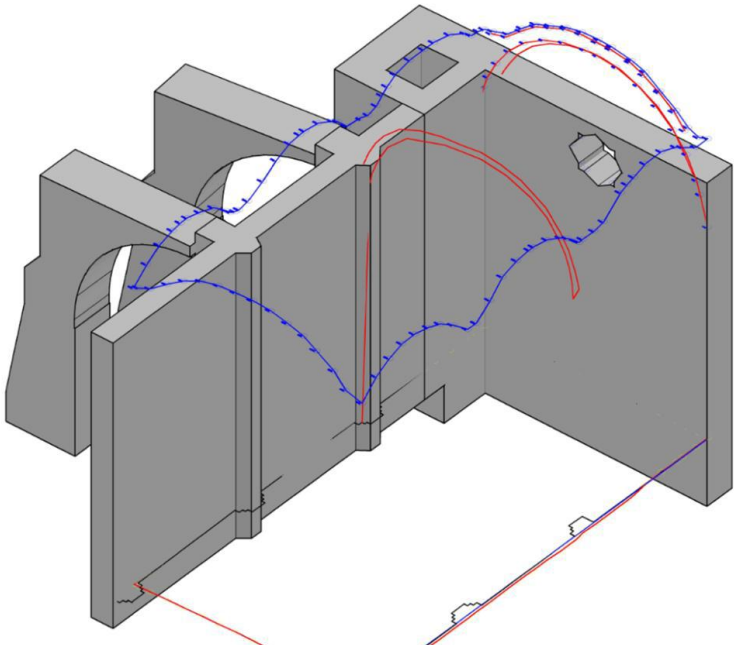

Figure 12: Geometrical model of the walls, tower and buttresses.

5 CONCLUSIONS

This paper presents the geometric study and finite element modeling of the ex-temple of Saint Augustine in the city of Zacatecas, Mexico. The geometry of the building was obtained from a topographical survey. This information is important for two reasons. Firstly, the actual deformations of the building can be evaluated and compare them with the deformations that will be obtained from the structural analysis; this with the purpose of evaluating the quality of the structural analysis. Secondly, the original geometric configuration of the building can be inferred and use it to generate the finite element models required to perform the building's structural analysis.

At the present time of writing this paper the modeling of the building has been concluded, missing only to perform the structural analysis. At this moment the following conclusion can be made:

- The arches and vaults of the central nave of the temple are very deformed. The central vault is the more deformed with a vertical deflection of 52 *cm* in a span of 12.0 x 7.7 *m*.
- A structured mesh to model the vaults was possible by dividing the geometric representation of the vaults in subdomains with ford borders. The mesh was generated with hexahedral finite elements of second order. This type of elements gives more accurate results than the tetrahedral elements used on anunstructured mesh.

AKNOWLEDGEMENTS

The use of the software MIDAS-FEA was possible thanks to the license provided by the company Bowerbird Ingenieria S.A. de C.V., this support is greatly appreciated.

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