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STRUCTURAL RESTORATION OF ANCIENT BASILICA DE GUADALUPE

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Abstract. *The Ancient Basilica de Guadalupe, today Expiatory Temple of King Christ, was built in 1709 by the architect Pedro de Arrieta.*
Throught the years, it has been affected by modifications and has suffered damages that have resulted in a loss of structural strength, and have diminished the architectural qualities that once made it a masterpiece of Mexican Colonial Architecture.
In 1994 it was decide to perform a total restoration of the monument to recover the original architectural values, and the structural retrofitting was essential to reach that then.
This document describes that retroffiting process.

1 STRUCTURAL HISTORY OF THE BUILDING AND CAUSES OF DETERIORATION.

The Ancient Basílica de Guadalupe, with its perfect and elegant symmetry, its four perimeter walls reinforced with buttresses, the four towers reinforcing the corners and its dome gazing to the sky, rising over a strong drum exactly of the center of the nave in what the Building Code for the Federal District would call in a rather vague way, “an ideal structure to withstand earthquakes”.

The two-meter thick walls, buttresses, vaults, and the dome were built with tezontle. Only the columns and arches in the structure are made of quarry, with the clear intention of reducing as much as feasible the weight of the construction.

If Pedro de Arrieta could visit his Shrine, he would find it almost as it was in 1709, when he delivered it; the only change being, the slight slope towards the entrance, produced by the soil subsidence that affected it in recent years, and the two lateral doors on the façade which were built when he was no longer present [1].

We would like to say that this was due to good maintenance given to the monument through the centuries, but nothing further from the truth; on the contrary, few monuments have undergone so many changes as this one.

Some changes were by natural causes and some others by unfortunate decisions, taken at different times in its history.

The first major change was in 1887, one hundred seventy eight years after the Basilica was enlarged. (Figure 1)

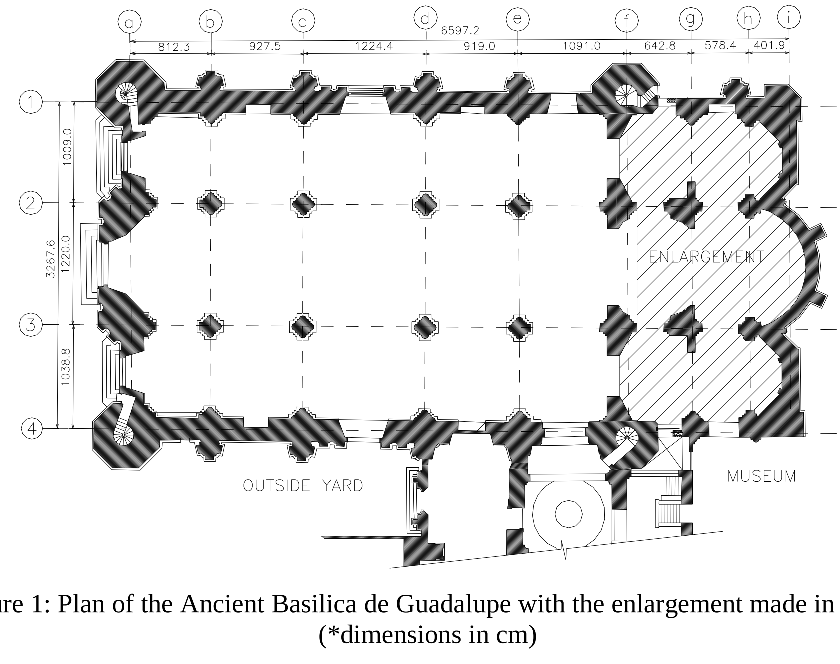

Figure 1: Plan of the Ancient Basilica de Guadalupe with the enlargement made in 1887. (*dimensions in cm)

It was decided to enlarge the Temple, and to this end, two bays were added to the North of the structure, that is, towards the Cerro del Tepeyac. In this way the Sanctuary lost one of its most important virtues: Symmetry.
Furthermore, as it would be appreciated several years later, placing the nave closer to the Cerro had an adverse repercussion on the performance of the building.

Forty-three years later, in 1930, two of the large columns built in 1887 were removed; and to perform this, without the slightest respect for the monument, there were placed metal trusses supported on columns of the same material which were embedded in the quarry columns, all these on a heavy underground foundation. (Figure 2)

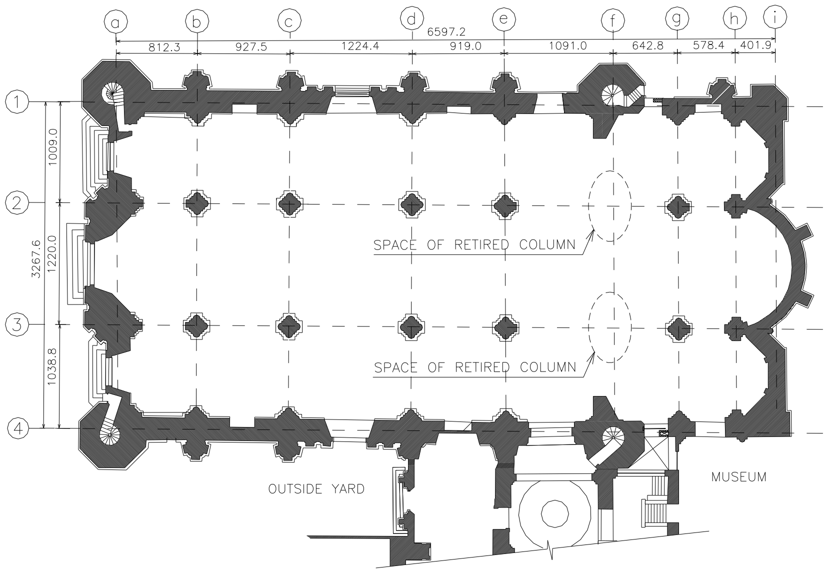

Figure 2: Plan of the Ancient Basilica de Guadalupe after retirement of two columns in 1930.
(*dimensions in cm)

The vaults of the ceiling were hung with tensors from the trusses, giving the Basilica an awful image that lasted for over sixty years.

Unrecorded interventions were done during the early twentieth century, for it has now been surprisingly found out that most of the vaults originally built with tezontle are now made of lightweight concrete.

All the other severe damages the temple suffered afterwards, even if derived from natural causes, were in the end, man-made in fact, due to the excessive extraction of groundwater for human consumption.

The bearing soil under the Basilica changes abruptly from North to South: Relatively shallow in the North extreme of the temple, it reaches a great depth under its Southern end.

Hence, the depth of the building’s foundation varies considerably, being shallower at the North, and quite deeper at the South (2.8 m to 7.0 m).

This difference in the depth of the bearing soil under the Basilica has caused extremely important differential subsidence, basically due to the extraction of the underground water which has been particularly intensive since the 1950s.

The continuous sinking of the Basilica caused new interventions on that building, retrofitting its foundations with a series of concrete beams attached to the original stone foundations, and with a large number of control piles [2]. These works, performed after 1965, slowed considerably the deformations that were being produced. (Figure 3)

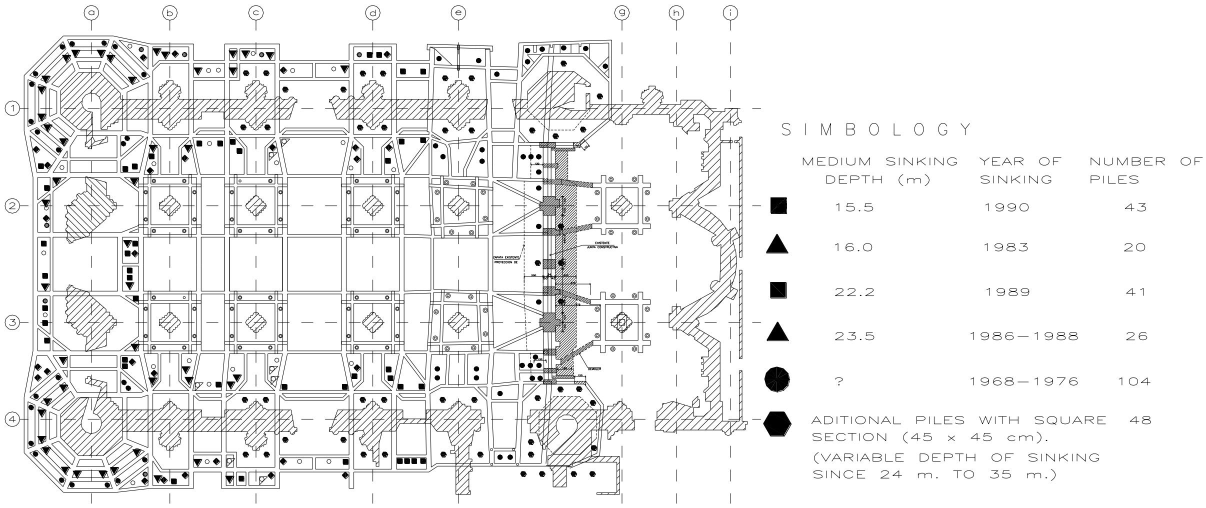

Figure 3:Foundation retrofitting of the Ancient Basilica de Guadalupe with foundation beams and piles of control.

Construction of the New Basilica and the surrounding underground parking places must have also contributed to control the long term movements which, in recent years, have virtually ceased.

During the works of retrofitting the foundation, it was decided to reinforce the columns of the Basilica, embedding them in a shirt of reinforced concrete. In subsequent analyzes and inspections it became clear that it was a preventive measure to protect them during the retrofitting works, as it could be shown that the coating is not structurally required and it was removed.

From 1994, at the time that the architect Sergio Zaldívar was in charge of Sites and Monuments of National Heritage, the restoration of the monument was begun with an excellent project by architects Jaime Ortiz Monasterio and Alberto González Pozo.

It was a long process that Ortiz Monasterio could not see finished. (Figure 4)

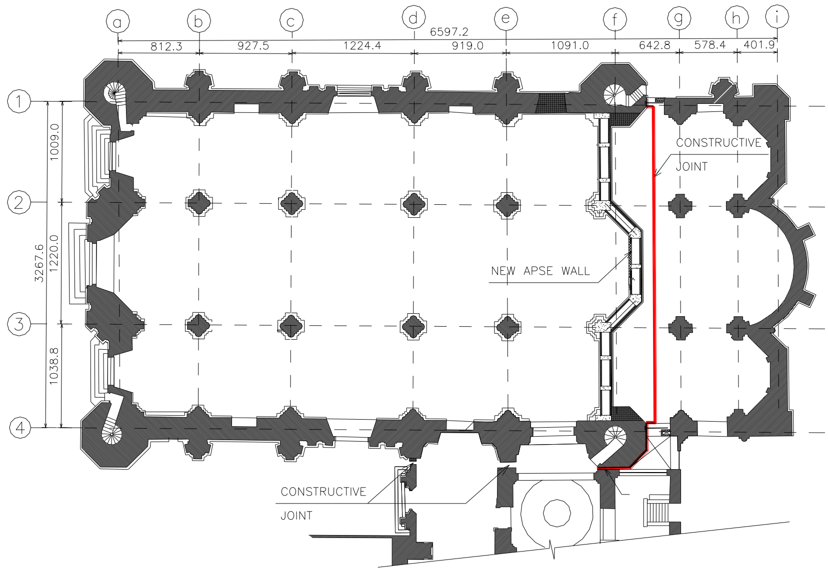

Figure 4: Recovery of the original geometry, new apse wall and constructive joint. (*dimensions in cm)

2 STRUCTURAL ANALYSIS.

To perform the structural analysis of the property in its current conditions, a three-dimensional finite element model using STAAD -PRO program was developed. It was based on the existing information of the geometry of the building and the information obtained from visits to the site. The model contains 8577 nodes, 868 members and 9220 plates.

The finite element method is a numerical method especially applicable to continuous structures that cannot be idealized as a series of bars, such as the skeletal structures of modern buildings.

The structure is divided into a series of linked portions in a way so that deformations in the binding links between portions are compatible with each other; in these conditions the structural analysis involves the solution of a very large number of simultaneous equations which can only be achieved by using a computer program. There are several fine commercial packages of easy application for finite element analysis, producing the results of the analysis both in a numerically and a graphical way, making it easy to observe the distribution and the value of the stresses in the structure as caused by the loads acting on it.

To this end, the STAAD-PRO program is one of the most used [3].

The model includes all elements that can be of significance to the structural response of the building, using the parameters of the geometrical and mechanical properties learned from the inspection results to the construction. (Figure 5)

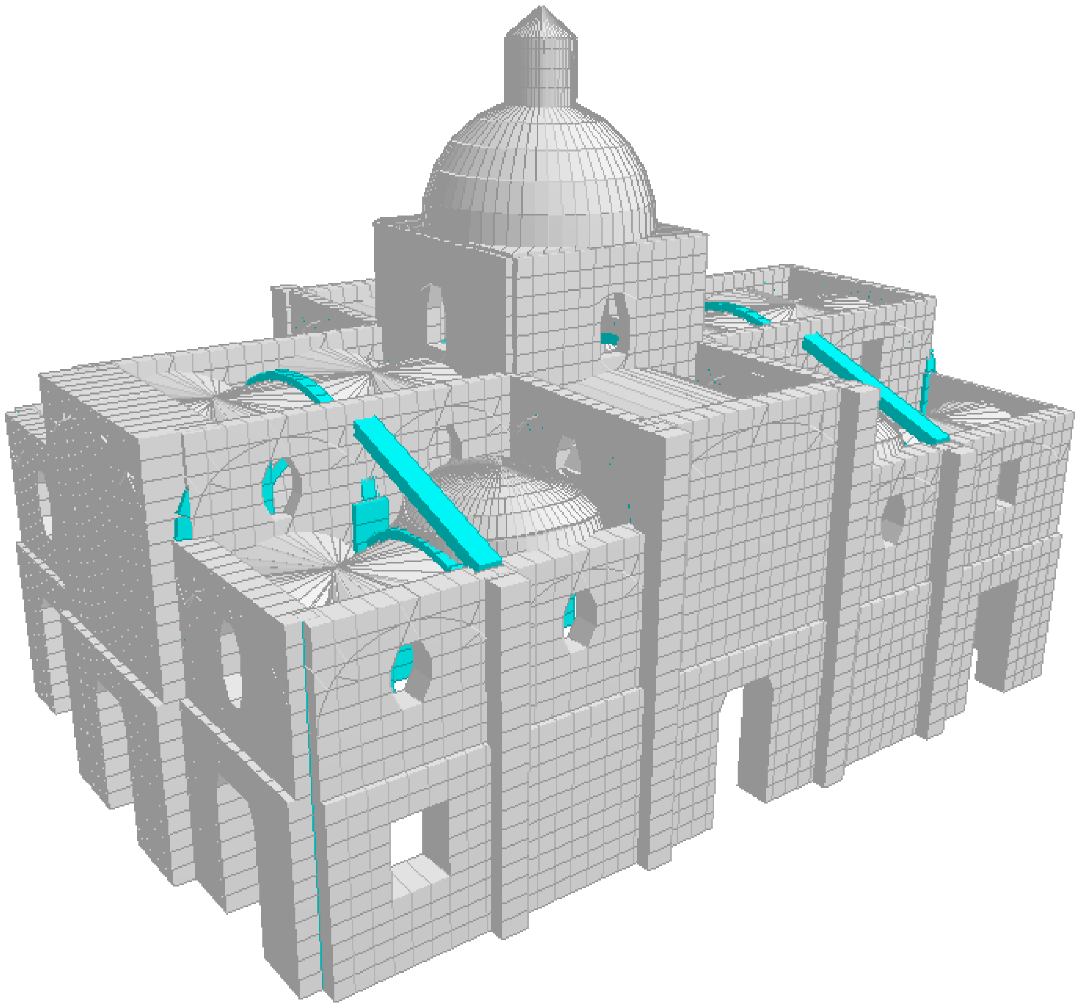

Figure 5: Model for analysis.

Given the characteristics of the structure, the most important element is the weight of the constituent materials; the live load is not significant.

The density of the stone materials was considered as 2.0 t/m3.

The seismic action considered corresponds to a very rigid building on a zone of high soil compressibility. It was considered a net seismic coefficient of 0.1.

The analysis is elastic, but the stresses are so low that they can be considered as a good approximation to those that might be obtained considering the true behavior that presents the material.

To determine the effect of the tilt on the existing building, two different models were developed.

The first was assuming a perfectly leveled structure, that is, as it was before tilted, and the second, considering the structure inclined as it currently is.

Both models were solved under the action of permanent and accidental loads, as required by Construction Code for the Federal District.

3 ANALYSIS RESULTS.

In the most unfavorable conditions, that is, under the action of seismic forces and considering the existing tilt, stresses are essentially compressive and their factored values of about 8.0 kg/cm², which is a considerably a lower value of what the structure's materials can bear. Only in some local areas there are tensile stresses with factored values of about 2.0 kg/cm² in vaults and 1.0 kg/cm² in walls. Both values are acceptable [4], especially considering the great thickness of the vaults and walls allowing the pressures produced by the applied loads to be invariably within the section of masonry. (Figures 6 and Figure 7)

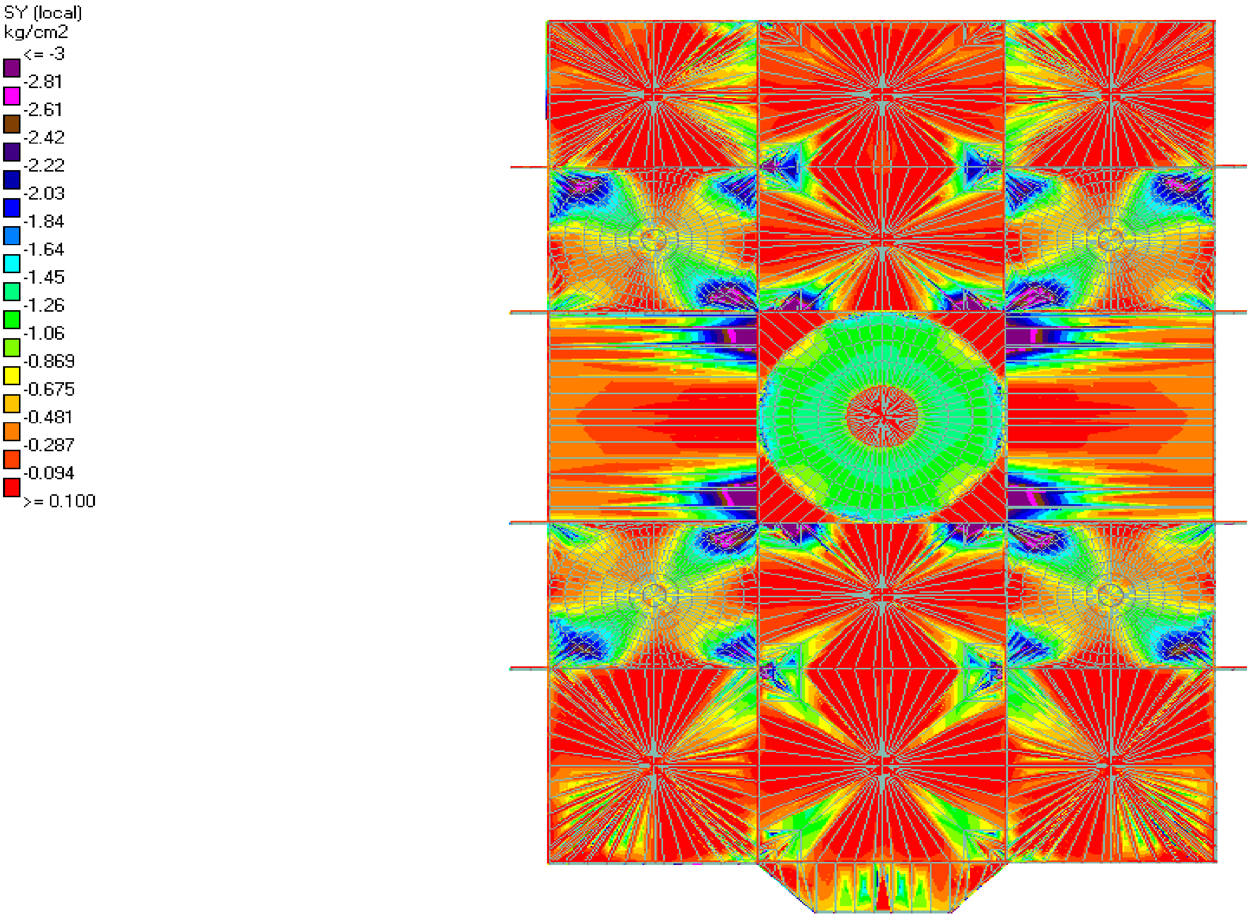

Figure 6: Normal stresses on the roof.

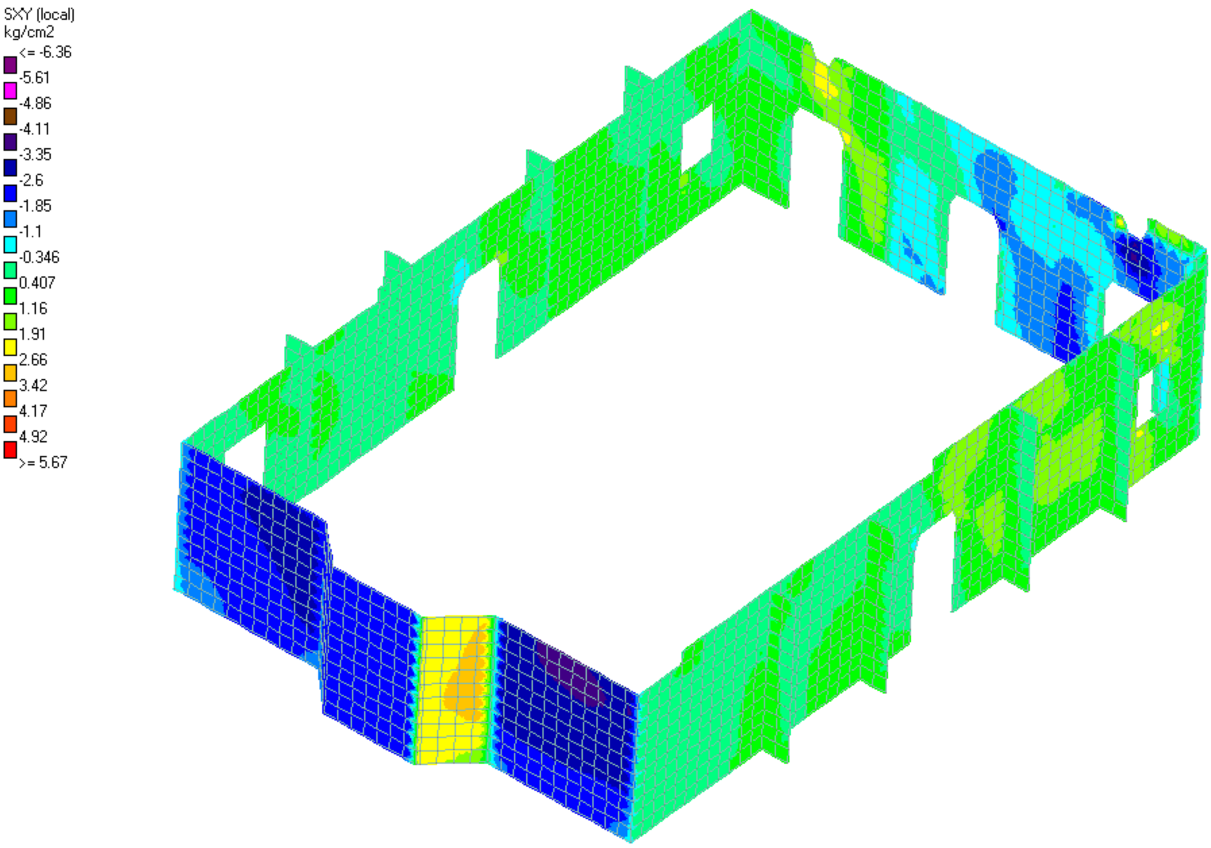

Figure 7: Shear stresses in walls.

Table 1: Comparison of mechanical elements (reactions) in columns of the transept made with the completely level structure and the inclined condition.

COLUMN	***COND.***	***Force-X (t)***	***Force-Y (t)***	***Force-Z (t)***	***Mom-X (t-m)***	***Mom-Y (t-m)***	***Mom-Z (t-m)***
NE	Horizontal	-30.07	726.39	-5.00	-20.68	2.37	193.65
NE	Inclined	-24.49	687.21	-27.06	10.43	11.71	242.74
SE	Horizontal	-26.32	738.06	-9.21	-35.84	-2.31	167.68
SE	Inclined	-20.82	709.59	-31.94	-4.42	4.15	211.09
NW	Horizontal	-17.38	695.46	-2.38	-3.52	0.97	135.77
NW	Inclined	-16.21	689.99	-26.48	14.09	9.63	206.54
SW	Horizontal	-14.00	684.83	-12.52	-56.18	-6.41	103.74
SW	Inclined	-10.55	675.70	-32.55	-15.02	-0.15	163.90

The computed deformations produced by the applied loads are negligible due to the high stiffness of the building.

A finite element analysis, assuming the continuity of columns, arches and ceiling, show axial loads and bending moments in the columns. The eccentricity of the axial load to the axis of the columns can be estimated by dividing the value of the bending moment by the load, and it is found that the resultant is always within de section of the columns and even that is practically in the middle third, implying that there are only compressive forces that the quarry can easily support.

4 CRITERIA FOR STRUCTURAL RESTORATION.

The basic criterion for the restoration of the building was the elimination of the causes of its deterioration.

The most important cause was produced by differential soil subsidence under the structure of the Basilica.

The structural restoration was performed in several stages through time, the first and most important given its magnitude, was performed in the early 1960's: To retrofit the building's foundation, a large number of control piles were placed. To achieve this, it was necessary to build a basement under the whole building, where the controls piles could be manipulated.

This sole action, however, was not fully effective, for the building kept having significant subsidence to the South-East. This was evidenced by several cracks on its the lateral walls, with the largest virtually matching the addition built in 1887.

Given all this, it was then proposed to divide the building in two parts on each side of said crack which, besides, was very convenient from the point of view of the building's general restoration, and gave place to the extraordinary project that was carried out.

On the walls, vaults and the foundation it was performed a construction joint.

It was constructed a new apse wall with the dimensions of the original, but now built with two brick walls spaced apart and well structured.

The metal trusses and tensors that held the ceiling vaults were removed and the vaults were rebuilt with the same geometric characteristics as the original vaults, but using a thin concrete shell.

A similar construction joint was performed in the northeast zone of the monument, in the place where it was linked to the former Chapel of Souls. Separation of the superstructure and foundation was an arduous process that, given the depth of the foundation, took several years.

The achievement of these works was to move the structure away from the hardest soil zone and make it also completely symmetrical.

The result has been to eliminate practically all of the preexisting differential settlements.

During the work performed on the 1960's, all columns were coated with a thick layer of concrete. In 1994 when the restoration work was restarted, there were no records that explained the causes for this coating. It could have been done as a preventive measure to protect the columns during such works; or it could have been reinforcement to prevent deterioration of the columns. The decision of whether remove the lining or replace it with some other type, was postponed till further analysis of the structure in its current condition, including the tilt it nowadays presents, was completed.

To proceed with the analysis it was first necessary to obtain the characteristics of the elements of the structure of the building [5]. (Figure 8, Figure 9 and Figure 10)

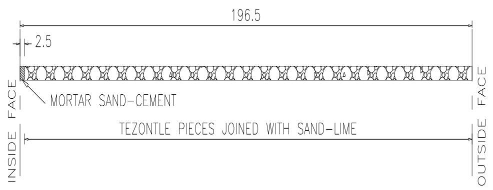

Figure 8:Tipical wall construction system.

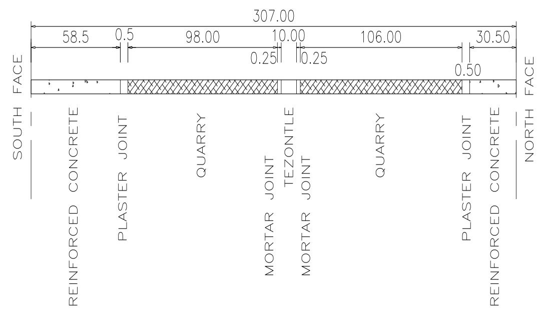

Figure 9:Tipical column construction system.

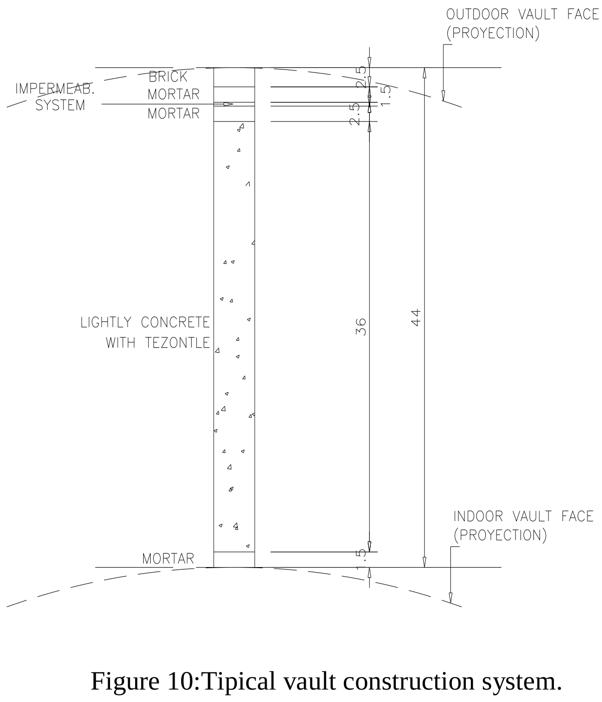

Figure 10:Tipical vault construction system.

(*dimensions in cm)

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