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Studies for the Rehabilitation of the Mexico City Cathedral

Etude pour la réhabilitation de la Cathédrale de Mexico

Studie zur Instandsetzung der Kathedrale der Stadt Mexiko

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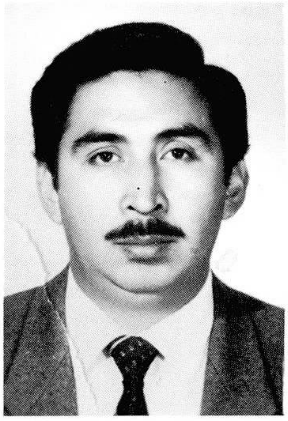

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SUMMARY

The Mexico City Cathedral is undergoing major rehabilitation work aiming at correcting its differential settlements, now reaching up to 2.4m. The most relevant structural investigations, performed to support decisions taken during the process, are briefly described; those related to assess the safety under vertical loads, the effects of the differential settlements and their corrections, and the seismic actions. Laboratory and in situ tests have been performed to determine the mechanical properties of the materials, the dynamic response and the state of stresses.

RÉSUMÉ

Des travaux considérables de réhabilitation sont entrepris sur la Cathédrale de Mexico afin de compenser des tassements différentiels qui atteignent 2,4m. Les études structurales les plus importantes, réalisées afin de contrôler les décisions prises durant les travaux, sont présentées; en particulier celles destinées à évaluer la sécurité, sous les charges verticales, des effets de tassements différentiels et leur correction ainsi que les actions sismiques. Des essais en laboratoire et sur place ont été réalisés afin de déterminer les propriétés mécaniques des matériaux, le comportement dynamique et l'état de contrainte.

ZUSAMMENFASSUNG

Grossangelegte Instanstellungsarbeiten werden an der Kathedrale von Mexiko ausgeführt, um den grössten Teil der beträchtlichen unterschiedlichen, bis zu 2.4m reichenden Senkungen zu korrigieren. Zahlreiche Konstruktionsnachweise dienten während der Ausführungsphase als Entscheidungsträger. Die wichtigsten werden kurz vorgestellt, jene betreffend den vertikalen Widerstand, das mechanische Verhalten, die Auswirkungen der Senkungen und deren Korrektur sowie das Verhalten bei seismischen Bewegungen. Tests im Labor und an Ort dienten der Bestimmung des dynamischen Verhaltens und des Druckwiderstands.

1. INTRODUCTION

The Mexico City Cathedral, probably the most important colonial monument in America, has been severely affected by differential settlements since the beginning of its construction in the 16^{th} century. The monument is extremely heavy (127,000 ton) and is located on very soft clay deposits, which in some parts had been previously consolidated by Aztec temples and pyramids over whose remains the Cathedral was erected. In this century the intense pumping of the underground water has severely aggravated the subsidence.

During the protracted period of its construction (240 years) the severe differential settlements forced the builders to significant adjustments in the geometry of the monument. After its completion, the Cathedral has been sujected to an almost uninterrupted activity of repairing, especially in order to seal the cracks in the roof to avoid leaking.

Presently, the building has reached a condition of distortion seriously undermining its structural safety. The maximum differential settlement has reached 2.4m and it is increasing at a rate of 1.2 cm/year. Some of the main columns supporting the roof show an out-of-plumb exceeding 2%. Severe cracks in the roof, floor and walls evidentiate the effects of the differential settlements.

Considering that the regional subsidence of the area will not be eliminated in the near future because water needs to be pumped to satisfy the demand of the city, measures had to be taken to restitute the building to a stable and safe condition. A major rehabilitation project has been started in late 1991. The main structural aspects of the project will be described here, focussing on the experimental and analytical studies performed. A description of the geotechnical problemas and of the subexcavation technique can be found in Ref. 1.

2. DESCRIPTION OF THE BUILDING AND ITS PAST PERFORMANCE

The temple is constituted by five naves. The roof of the central nave is formed by a cilindral vault supported by arches and by 16 stone columns. The lateral naves have hemispherical vaults. A close array of robust masonry walls divides the extreme naves in small chapels. These walls along with the facades and some buttresses constitute a peripheral belt providing great lateral strength and stiffness to the monument. A large dome at the intersection of the central nave and the main transverse nave, constitutes the heaviest and most critical part of the roof. The main features of the construction can be appreciated in Figs. 1 and 2. The structure is supported by a grid of foundation beams (3.5 m deep) and by a foundation mat with a thickness of about 2m. Timber piles (with a diameter of 0.2m and a length of 2-3 m) are spaced every 0.6 m underneath the foundation mat.

The primary construction material is a kind of poor concrete constituted by volcanic stones, of different size and unit weight according to the structural member, agglutinated by a lime-sand mortar. The properties of this material will be discussed later. In arches and columns andesitic stone sills were used.

Large differential settlements started since the early stages of construction, as evidentiated by the many significant adjustments made to the dimensions and shape of the construction members. For instance, the length of the column varies according to the settlements experienced of their bases at the time when the arches and vaults were built. The maximum differences being 0.85 m. Several rows of sills with variable height were placed at the facade to correct the inclination

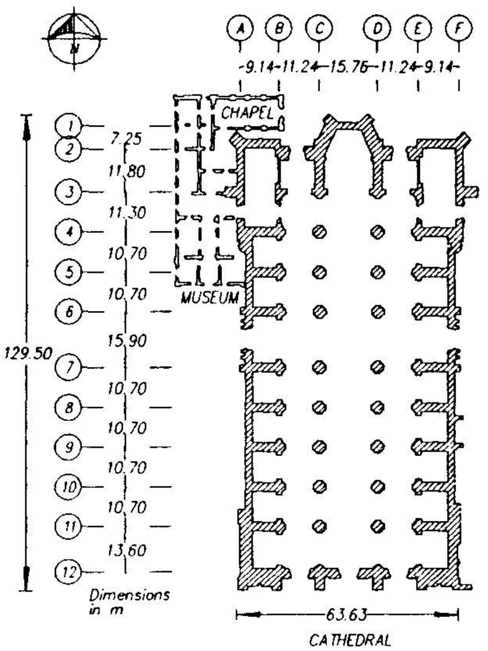

Fig. 1 Plan view of the Cathedral

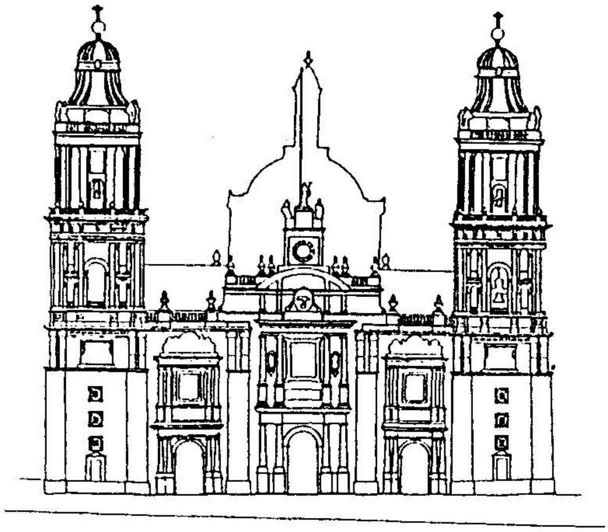

Fig. 2 Front view

at the time of the construction. The span and rise of the arches and vaults were varied in order to achieve an almost flat roof. After the completion of the roof, the structure adquired a greater stiffness thus the differential settlements increased at a lower rate. Nevertheless the large cracks and the inclination of the upper parts of the columns reflect the very large distortions suffered by the structure once it was completed.

Fig. 3 shows the pattern of differential settlements measured in the floor of the Cathedral some time before at the beginning of the rehabilitation work (late 1989). Another useful representation of the phenomenon is given by the curves of equal rate of differential settlements in the year before the commencement of the works (Fig. 4). Two major mechanisms of deformation can be appreciated. One is the sinking toward the Southwest corner, another is the "emergence" of the central nave in the Northern part.

The first mechanism has produced a pattern of transverse cracks in the roof and walls, especially near the central dome, and some separation of the Southern facade, with its very heavy towers, from the rest of the church.

The second mechanism produced the outward rotation of the columns and lateral walls, and the opening of the vaults and arches in the roof, originating a pattern of longitudinal cracks in the roof, floor and foundation. This second mechanism is the most critical from the structural point of view, because of the inclination of the columns receiving the greatest vertical loads, especially those supporting the central dome. As can be seen in Fig. 5, the present shape of the column shaft shows changes of direction due to corrections made during the construction. The total eccentricity between the upper and lower part of the column is, for this case, 0.6m representing 25% of the size of the column. Some vertical cracks at the upper part of the column are attributed to the compressive stresses generated by the eccentric compression.

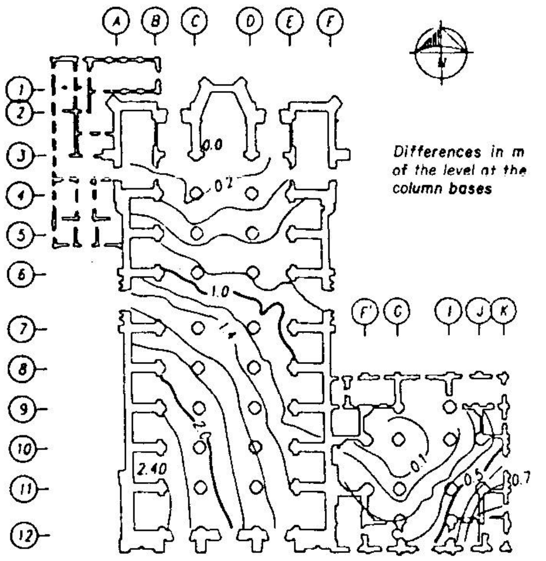

Fig. 3 Differential settlements (Dec. 1989)

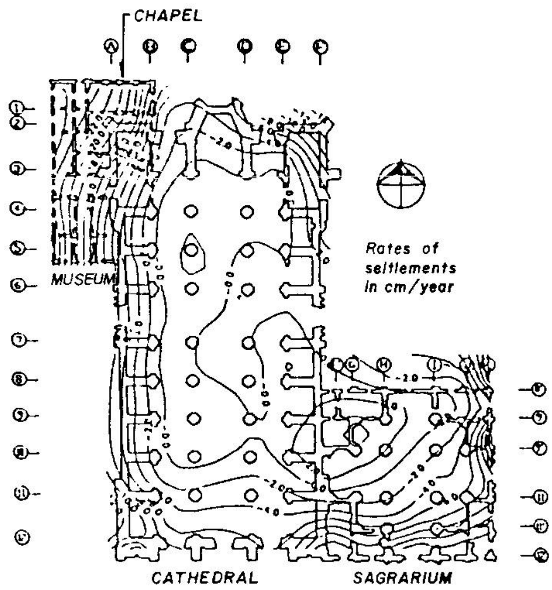

Fig. 4 Annual rate of increase in differential settlements (1991)

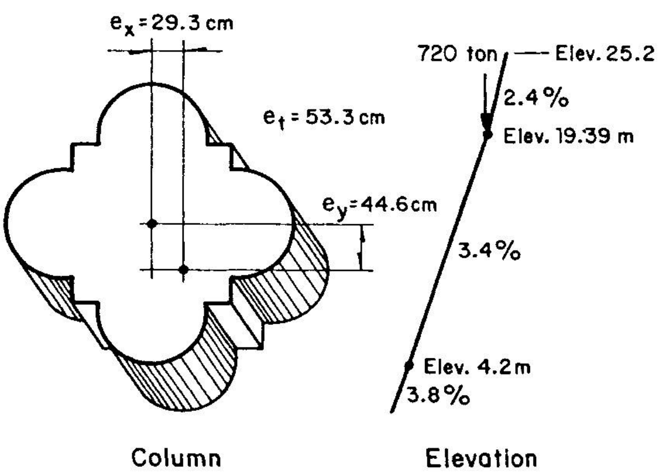

Fig. 5 Deformed shape of a central column and applied forces due to self-weight

3. ASSESSMENT OF THE STRUCTURAL SAFETY

The self-weight of the temple represents a very severe action on the foundation and on the soil. Its effect have been studied by a finite element analysis of a tridimensional linear model. The same model has been used to analyze the stresses induced by displacements of the supports, representing simplified patterns of the differential settlements suffered by the building, as well as of the motions to be induced by the correction process.

A thorough view of the state of stresses induced by the vertical loads in the central part of the monument is shown in Fig. 6. A move schematic representation of the flow of forces in members supporting the central dome is shown in Fig. 7. It can be appreciated that the weight is transmitted toward the foundation essentially by axial forces in the vaults, arches, columns and walls. The level of stresses in the members of the original structure disregarding the changes in their geometry due to settlements and adjustements, is well within the range of capacity of the materials.

The outward motion of the supports in the Northern part of the central vault has produced a mechanism of non linear

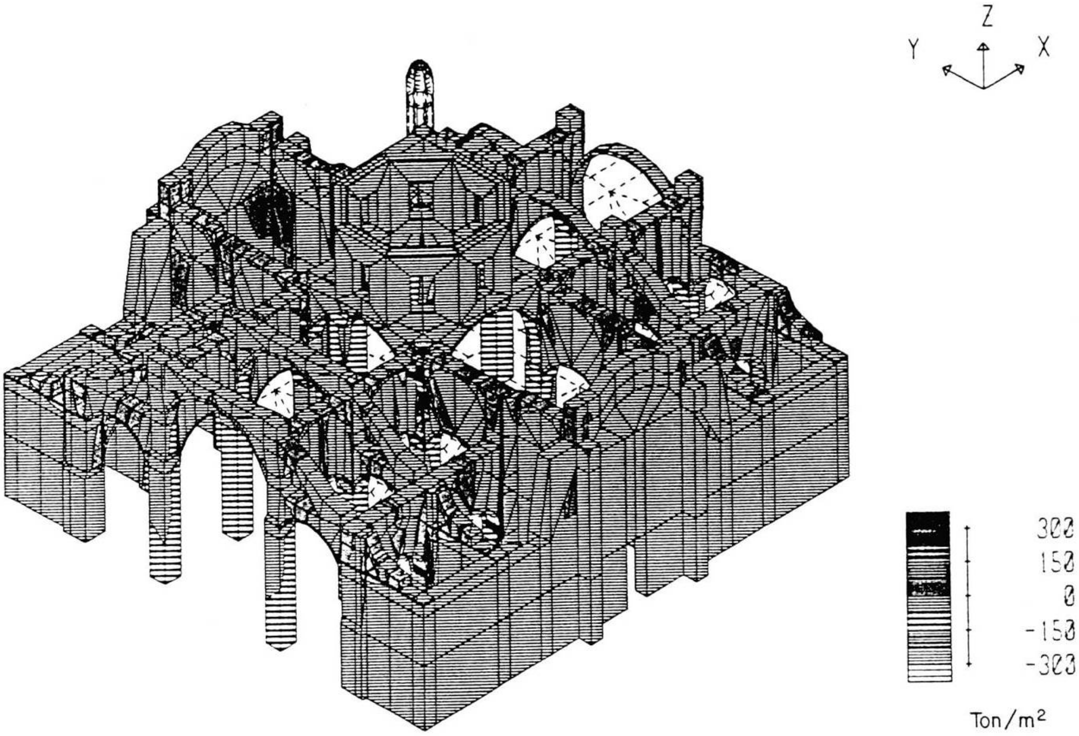

Fig. 6 State of stress due to gravity loading from a finite element analysis of the central portion of the Cathedral

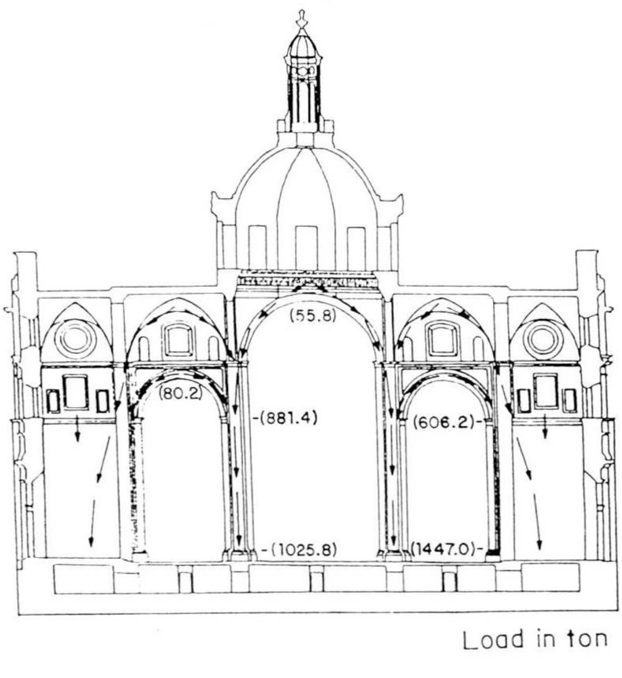

Fig. 7 Flow of self-weight loads in the zone under the central dome

deformation as the one schematically shown in Fig. 8. The present deformed shape of the vault is still well within a stable configuration. On the contrary, the analysis of the stability of the central columns shows that bending moments induced by the eccentricity of the force produced by the weight of the roof, increase the maximum compressive stress 2.3 times above that computed for the undeflected shape of the column. In this fashion stresses are now very near to the maximum capacity of the stone.

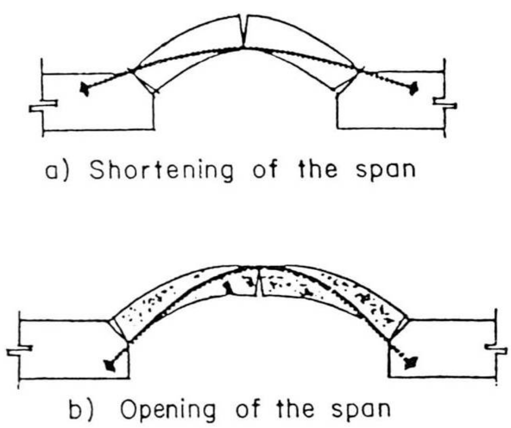

Fig. 8 Mechanisms of inelastic deformations due to movements of the supports of the central vault

The seismic safety of monumental structures like the Cathedral cannot be assessed by the procedures prescribed by building codes for modern structures. It must be considered that the actual shaking induced in these very heavy and stiff structures founded on a very soft soil is much smaller than for ordinary buildings, because a significant part of the energy that the ground tries to impose to the structure in actually returned to the soil through radiation. Additionally, part of the seismic energy can be dissipated through opening and closing of cracks, through relative motions between parts of the structure and through uplifting. For these reasons monumental buildings have shown an outstanding capacity to withstand severe earthquakes in Mexico City, even when modern and apparently stronger structure have been badly damaged. Earthquake damage of monuments has been generally associated to cases of extreme degradation of the materials or to severe previous damage due to differential settlements.

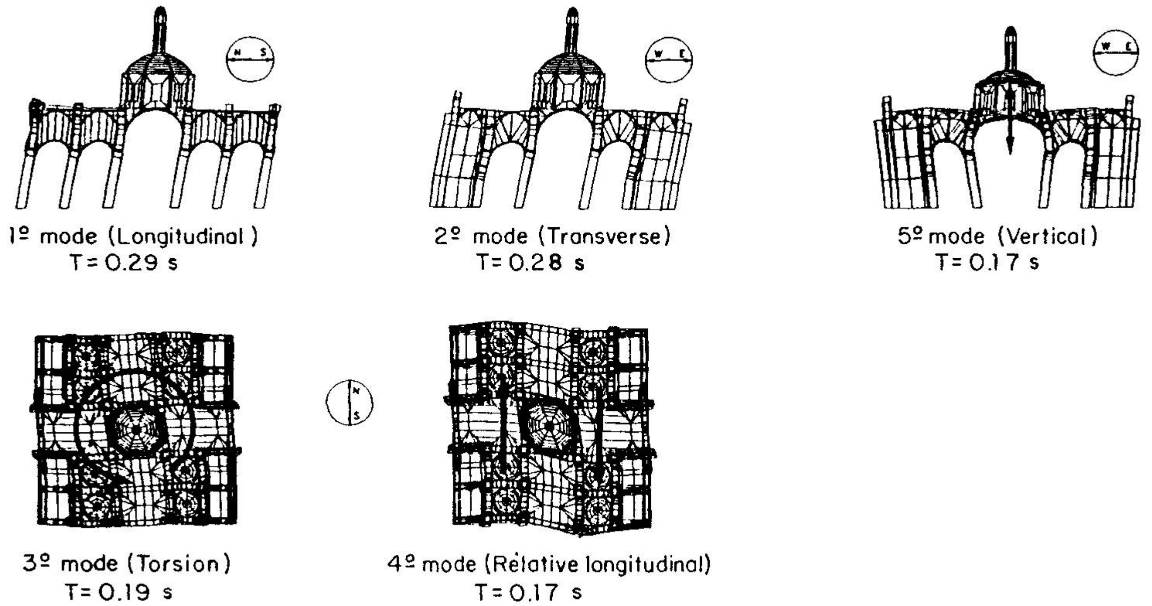

Fig. 9 Modal shapes of vibration from a finite element model of the central portion of the Cathedral

The previously described linear elastic tri-dimensional model was used for a dynamic analysis to compute the modal shapes and periods of vibration (Fig. 9). It was found that in plan deformations of the roof favoured torsional modes of vibration and that the large concentrated mass of the central dome produced significant vertical vibration. Computed periods were compared with those derived by measuring the vibration of the building in ambient conditions. Consistently, computed periods are smaller than those measured. This is attributed to the lack of fixity of the base of the structure where the foundation allows significant rotations of the walls and columns. Additionally, the extense cracking of the structure significantly reduces the stiffness, thus increasing the vibration period.

For the assessment of the seismic safety, a constant spectral ordinate of 0.2m was assumed. It was considered that, because of the existing cracking and of the small tensile strength of the materials, parts of the structure could vibrate independently from the rest. Therefore, the seismic safety of the most critical portions was assessed primarily by simplified methods. In general terms, it was concluded that the strong peripheral belt constituted by the facade walls and by the walls sorrounding the chapels provided a satisfactory overall safety. Nevertheless, the additional lateral displacements of the columns during their seismic vibration could lend to their lateral instability and to a local collapse.

4. CORRECTION OF DIFFERENTIAL SETTLEMENTS AND ITS EFFECTS ON THE STRUCTURE

As shown in the previous section, in its present condition the Cathedral is structurally unsafe due mainly to the great inclination of the central columns, and the operation of the temple is greatly impaired due to the excessive slope of the floor and to the great cracking.

After evaluating several alternatives, a technique called "subexcavation" was adopted to correct parts of the settlements. Briefly, a controlled subsidence of the most elevated parts of the ground is produced by the extraction of soil from the deep strata of soft clay. As shown in Fig. 10, small diameter radial boreholes will be excavated from 23 shafts opened to a depth of about 20m. The closing of the holes due to the weight of the soil and structure produces a settlement at the surface. Through a careful programming of the amount and position of excavated soil a preselected configuration of ground settlements can be achieved with great precision.

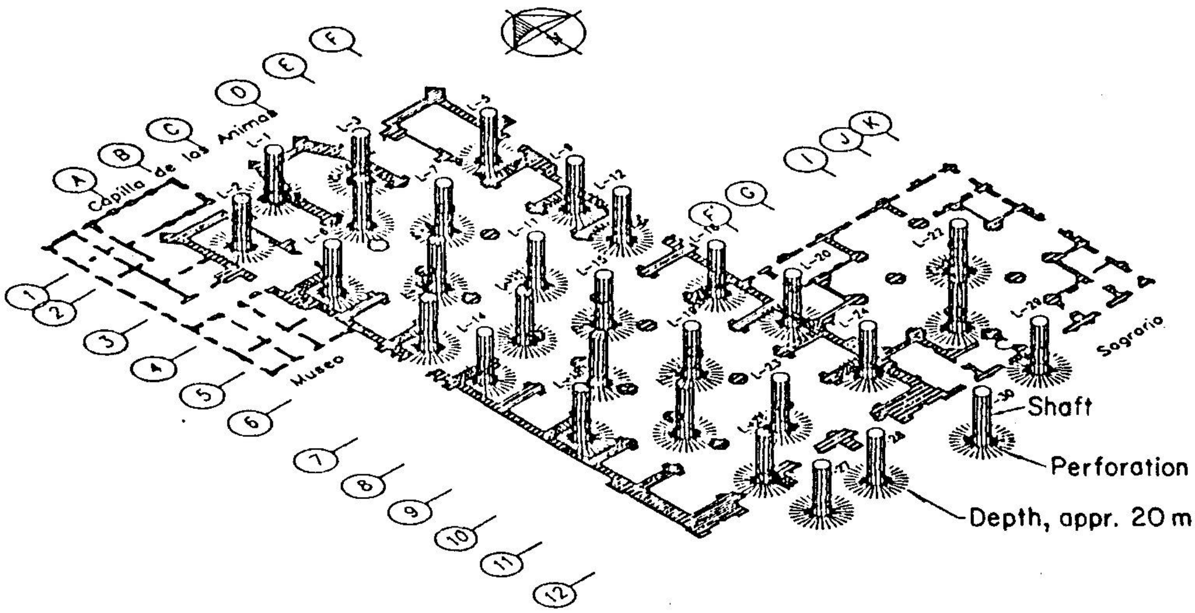

Fig. 10 Position of the main shafts and radial perforations for the correction of the differential settlements

The technique has been already applied to correct other modern and ancient buildings. At the time of writing this paper the 23 shafts beneath the Cathedral have been almost completed. In mid 1993 the subexcavation will be started to produce first a gradual settlement of the Northern part of the temple in order to correct the first mechanism of differential settlements which is quantitatively the largest, but structurally the less dangerous. Then, the second mechanism of differential settlements will be corrected, essentially by producing the inward rotation of the lateral naves in the Northwest part of the temple. The process will be carried out in several years in order to maintain a very slow settlement rate that will minimize the structural damage.

The effects of the corrections on the structure are being carefully analyzed. In general terms, it is expected that the correction of the first mechanism will produce a significant transverse cracking of the roof and walls. Provisions will be taken to avoid the complete separation of the very heavy Southern facade from the rest of the structure. More critical is the correction of the second mechanism which will tend to close the span of the central nave and to upright the columns. Because the cracks formed when the arches opened, have already been repaired, the closing can only be reached through the formation of plastic hinges in the arches as schematically shown in (Fig. 8).

Undoubtedly, the structural damage will be significant, but, as the structure is thoroughly shored, no danger of collapse is foreseen. Nevertheless, the only way to prevent an undesirable behavior is by a close monitoring of the building response.

5. STRUCTURAL MONITORING AND TESTING

Several parallel measurement systems have been implemented to monitor the displacements of the structure. Bimonthly levelling of the position of several hundred points of the structure is performed through high accuracy surveying. Additionally, the inclination of the columns at different heights is being monitored through electronic inclinometers. The position and width of cracks in the main structural elements is checked every month. All the information is processed in a computer system providing maps and graphs of the deformations.

Additionally, some more sophisticated, special purpose measurements systems are being implemented. The loads taken by the shoring towers are determined by measuring the unit strain in the vertical pipes through 312 strain gages. 12 high sensitivity inclinometers provide a continous record of the motion of critical points of the roof, columns and floor, allowing the detection of sudden motions. They are also used as vibration transducers. An additional system providing continous record of the motion of the columns and of the changes in the span of some arches will be installed soon. Flat jacks are been placed in some columns and walls to monitor the state of stresses.

The mechanical properties of the main structural materials have been directly determined in the building. Samples have been extracted from columns and walls to determine unit weights, moduli of elasticity, and compressive and tensile strengths. Despite of a significant variability, the quality of the construction materials can be considered to be very good.

6. CONCLUSIONS

The rehabilitation technique adopted has never been used before for a building of this size, complexity and materials. Therefore, the detailed analysis of the effects and the close monitoring of the structural response are essential in order to select the most convenient and safe program of work. Up to this moment, the results have been completely satisfactory, nevertheless the most critical part of the process is still to come.

REFERENCES

1. Tamez E., E. Santoyo and A. Cuevas, "The Metropolitan Cathedral in Mexico City, Correction of the Behavior of its Foundation", Mexican Society of Soil Mechanics, Mexico, aug 1992.