STUDIES OF GAUDI’S "CRIPTA DE LA COLONIA GÜELL"

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SUMMARY

The Crypt of the Colonia Güell is only the existing part of an unfinished construction imagined and commenced to be erected under Gaudi’s direction during the period 1908 to 1915. Once finished, it would have been the church of the Güell Factory’s Village in Santa Coloma de Cervelló, near Barcelona. A remarkable feature of this building is found in the use made by Gaudi of a tridimensional funicular model to design the geometry of its unique structural system. The strings in the model were materialized as a hierarchy of diafragms, arches, and oblique pillars made of brick fabric and stone. Due to this design, the theoretical stability of the building should be largely dependent upon the achievement of a funicular-type balance of forces among all the elements of the whole structural system.

A numeric analysis, based on a Generalized Matrix Formulation, was performed to study in detail the today actual resisting mechanism under gravity loads for the built part of the structure, as a way to measure the alteration of the funicular equilibrium and relate it to the damage that is observed. Long term phenomena like mortar shrinkage were also incorporated in the study and found very significative. Through the comparison between the numeric predictions and the observed in-situ damage a new understanding of the real state of the structure and actual resisting mechanism were obtained. Particularly, the stability of the structure was demonstrated as a result of the capability of the building imagined by Gaudy to adapt to different states of equilibrium throughout the hypothetic complete construction process.
Fig. 1.- The entrance to the Crypt under the portico

THE BUILDING AND THE FUNICULAR MODEL

The Crypt of the Colonia Guell is the only part actually built of what was to have been the parish church of the model Village founded by Eusebi Guell in 1890. Gaudi was commissioned to design it in 1894, when he was also working in the Expiatory Temple of the Sagrada Familia. The foundation stone of the Church was laid in 1908. Gaudí spent fourteen years to lay out the structure, due to which its construction was not started on until The works were abandoned in 1914, leaving only the crypt and the portico finished (Figs. 1, 2). It is located in Santa Coloma de Cervello, just a few kilometers from Barcelona.

The general form of the floor plan is oval, with a star-shaped outline (Fig. 2) and it measures 26 by 63 m. The used materials are mainly brick fabric and stone. The slab roof is supported by an eskeletal system which consists of a hierarchy of ribs, arches and columns. Some of the columns are oblique. The external walls of the crypt itself reveal elevations with different inclinations in such a way that the base of these configures the star-shaped perimeter;
the upper part of the walls are pierced by rhomboidal windows. On the south facade there is the portico, its roof consisting of of hyperbolic paraboloids made of brick masonry. This was intended as the access to the church, located to the floor above.

The central nucleus is delimited by four basalt columns and the arches which separate it from the choir, all of them angled in towards the centre of the nucleus, and two peripheral aisles forming a double semi-circle around the nucleus (Figs. 3,4). Columns and pillars support the main brick arches from which the ribs spring. These are also of brick, and have been treated in two different ways; those which converge on the two circular bosses — linked by a practically flat brick arch— consisting of a brick rowlock arch 15 cm thick, supporting a wall of the same thickness. The remaining ribs are walls 12 cm thick,
but raised over brickwork over brickwork arches three courses thick. The reticulum formed by the ribs is flush at the same level and supports the solera or masonry floor slab (Fig. 5). It consists of a first triple layer of facing brick, with a suspended floor over this, formed by brick partitions, supporting the final double layer; presumably, the paving of the church was to have been laid over this.

Fig. 3.- View of the central columns

The limitations of the graphical or numerical methods available to Gaudi, obliged to him work out his stereo-funicular structure using a physical scale model. Thus, Gaudí developed a tridimensional funicular model in which strings were used to represent actual brick masonry arches and oblique brick or stone columns (Fig. 6). In fact, the whole arrangement of columns, arches and ribs is the materialization of the funicular model which Gaudi built and studied over the ten years before its construction was started on. There is small doubt that the crypt is the first large structure laid out based on a similar three-dimensional funicular model, were funicular lines interweave in the three spatial dimensions. More details in regard to historic or construction aspects may be found in Casals et al. (1990) and González et al. (1993).
During the Spanish Civil War, the original hanging model was destroyed and just a few photographs of it survived. However, thanks to the initiative and the huge task of a group of Dutch and German admirers of Gaudi, we now have the reconstructed version of it (Tomlow, 1989). Besides, the correlation demonstrated by comparing photographs of the new model and that by Gaudi permits reasonable speculation about the new images of the unbuilt part.

The inclination of the columns in the crypt was imposed by Gaudi for compositional reasons, and it was achieved thanks to the thrust generated by the arches or ribs which would support the floor of the church. Surprisingly, the actual inclination of those columns in the built structure is higher than the one observed in the funicular model.

Thus, the comparison between the reconstructed model and the actual building arises some doubts. If the structure is in equilibrium at the moment, with lines apparently distant from the funicular model, ...would it be in equilibrium once it was finished?
We have here precisely the great paradox of the crypt. It is a building which was conceived to be stable once it was finished, but nevertheless it is stable now, in its unfinished state.

**ABOUT THE ACTUAL STATE OF THE BUILDING**

However, one may still think that the structure behaves according to the funicular model although only partially. This may be deduced from an indicator which has generally been overlooked but is of considerable importance when it comes to checking the possible hypothesis about the behaviour of the building: the intricate pattern of cracks in the facing brick ceiling or solera which covers the central nave, and those which affect several of the ribs and some of the arches.

Detailed analysis through direct observation and an exhaustive photographic survey of over 1000 images has enabled to determine the patterns of
cracks reproduced in Fig. 8, which is only an overall view amongst all those that were detected.

The building has not collapsed, but neither can we say it is undamaged. The detailed inspection of the structure through direct observation and photographic survey has enabled to determine the pattern of cracks which is partially reproduced here (Figs. 7,8). Those cracks could be seen not only in the continuous slab of brick masonry over the crypt, but also in the secondary arches or ribs.
The structural analysis of systems composed of curved members such as the arches, diaphragms or nerves which may be found in many ancient structures, is commonly carried out using the finite element method with isoparametric type with displacements as unknowns. It may be seen that, due to the deficiencies of the method in the description of the internal equilibrium of the elements, accurate results of internal forces are only obtained when a considerable amount of individual elements are used in the geometric discretization. However, for structural systems composed of unidimensional curved members, it is possible to establish analytical generalizations of conventional matrix methods based directly on exact equilibrium. Although the practical use of these matrix formulations was limited in the past by the large volume of mathematical operations required, recent developments in digital computers make this point less critical nowadays, while the aspects of accuracy and versatility gain renewed interest.

The analytical model used in the studies presented is directly based on a Matrix Generalized Formulation specifically developed to treat ancient
buildings consisting of multiple structural systems with curved, variable cross section members. The formulation, initially based on the work of Baron (1961) for static linear analysis, has been extended to nonlinear geometric and modal vibration analyses. Relevant aspects of the resulting method are the following:

(1) Automatic generation of complex geometries throughout the length of the element. Three cross sections, having arbitrary shapes, are to be given at three respective points of the axial curve of each element.

(2) Each different cross-section is defined as a composition of elementary trapezoids, where each of them may be associated to a different type of material.
(3) Specific devices are included to model load bearing or shear walls as equivalent systems of linear elements according to the method proposed by Kwan (1991).

(4) Nonlinear geometric analysis based on an updated Lagrangian formulation, thus allowing the treatment of cases involving instability phenomena of arches or other curved elements.

(5) Modal dynamic analysis based on the formulation of a consistent elementary mass matrix which objectively takes into account the distribution of mass and stiffness throughout the element.

Constitutive equations for brick or stone masonry at the macro-modeling level are now being implemented in the general model so that an integrated nonlinear geometric and material nonlinear analysis method will be available in a short time.

Nevertheless, the linear elastic analysis carried out for the Crypt, as described in the following sections, was very informative and revealed itself suitable to obtain an interesting understanding of the actual state of equilibrium of the building, as well as to investigate the causes of the existing damage.

Before its systematic use for the study of existing buildings, the model, implemented in the computer program CRIPTA, was checked through the analysis of a series of simple and multiple systems of curved members, for which analytical or experimental results were available. The comparisons, described by Molins et al. (1994, 1995), showed the very satisfactory level of accuracy and numerical efficiency which are achieved even for geometrically complex structures.

NUMERICAL MODELLING AND RESULTS

In order to reach a better understanding of the present state of the structure and also understand its actual equilibrium, it was decided to carry out several computer analyses. The first type of analysis was based in plane stress and was used to study the individual elements like ribs. Due to time limitations, it is not presented here.

The second type of analysis was a global one using the above mentioned Generalized Matrix Formulation (implemented in computer program
The structural members were treated as linear elements with curved centroidal axes, as well as arbitrary cross sections, thus allowing to model the arches, ribs, diaphragms and columns incorporated in the existing structure. This allowed to accurately take into account their actual stiffness. Thus, the model shown in Figs. 9,10,11 was constructed from the elevation and other disposable information. In addition, solid undeformable elements were introduced to simulate the massive capitals were columns, arches and ribs connect.

The adopted formulation made it possible to reproduce states of stresses caused by combined axial, shear, bending and torsion forces, and thus to simulate possible modes of global equilibrium more complex to that of a funicular model, having also into account the actual distribution of stiffness between structural elements.

The lead joints which exists at the junction between the central columns and their pedestals and capitals, were treated alternatively as perfectly fixed or rotational free hinges. First, the existing part of the structure was studied subjected to the vertical load produced by the weight of the eskeletal system of ribs, arches and columns as well as the weight of the upper slab, which
rests on the first. By this study, the zones subjected to high tension stresses were recognized.

The tensional stresses obtained in the different elements are mainly caused by their individual behaviour under vertical load, and are hardly influenced by interacting forces due to global effects. Thus, the highest tension zones appear at the joints between ribs and capitals or arches, and lower tension zones appear at the middle of the span of ribs.

Moreover, a correlation was found between the analytical prediction of high tension levels and the cracks observed in the structure. However, the first showed many other potentially cracked zones which were apparently intact in the building. These are interpreted as parts which, although cracked, do not show an evident structural damage or which, although intact, are subject to a high level of stress and might be easily damaged by overloading or altering the present geometry of the structure.
Fig. 11.- View of the numerical model (with stress intensities represented in chromatic scale)

THE RHEOLOGICAL ACTIONS

There are also radial cracks in the upper slab which cannot be explained by the gravity forces. Having discounted other causes, the only probable one is hydraulic shrinkage.

The values which are habitually handled to dimension the movement due to hydraulic shrinkage in masonry structures range between 1 and 7 yo 8 tenths of a millimetre for each linear metre of wall. No values have been found which refer to sheer brickwork elements, since this is a construction procedure which is not ordinarily used, and on which tests have not been generally been carried out. However, the values could not be lower in view of the larger relative proportion of mortar in the section, as well as the great proportion of portland cement in the mortar.

In fact, the R-X diffractometric analysis of some mortar patterns showed that, surprisingly, it consisted of almost pure Portland cement. This is against the usual technique for building such a brick roof or vault at that time, since
the first skin was always treated with plaster to avoid the use of scaffolds and forms.

Moreover, the measurement of the total width of the cracks amounts very closely to the shrinkage contraction that could we expected for such a mortar.

Hence we can draw a further conclusion: contraction is the process which makes visible many cracks of gravitational origin, or contributes to their appearance when it is added to the mechanical tensions in the cases where tension in the ribs and foreseeable lines of fracture in the upper slab coincide.

Fig. 8 represents a plan of the solera which shows the gaps provided to leave room for the columns of the church above, which no doubt is relevant to the matter of shrinkage. On this plan, if we observe the numerical forecasts and the present evaluations which recommend the provision of walls with expansion joints every eight metres, and if we look for the areas where, because of their smaller cross-section and a geometry which might provoke cracking, assuming a uniform grid, we reach the conclusion that it was to be expected that tensions would occur along these lines.

To all this should be added the plan showing the areas where, according to the computer model, the upper part of the ribs is under tension. If we assume complete adherence between the ribs and the solera, we may suppose that this tension is transmitted to the latter. Hence, in addition to the tension due to hydraulic contraction we must consider the tension due to mechanical behaviour under gravity. Due to the fairly considerable correlation between the hypothesis and reality, we may conclude that the radial cracks are due to contraction, while the cracks between the heads of the columns, the capitals, are due to a combination between contraction and tension or flexural phenomena due to the gravity loads of the rib arches.

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CONCLUSIONS

These studies and considerations allow us to present some conclusions upon the actual state of the structure and also about the hypothetical complete building. First, the building is stable under its own weight and the permanent
loads at present affecting it. This is so in spite of the fact that the present loads were the cause, at some time, of the existing damage. The overall stability is more than assured, thanks to the strength of the interior columns and the perimeter walls.

![Diagram](image1)

**Fig. 12,a.- Movement of the central nucleus under today's dead load**

![Diagram](image2)

**Fig. 12,b.- Movement of the central nucleus under the effect of concentrated loads simulating the completion of the building**

The obtained scheme of forces at the level of arches and ribs keeps similar to that of a funicular type of equilibrium, although the geometry does not correspond to that of the funicular model. It may be seen that, owing to their much larger sectional dimensions, the deformations of columns and the perimeter wall are very small in any case, so that the equilibrium of arches and ribs is not affected by the fact that the devised global structural system is not completed.
When lead joints are treated as perfect hinges, a significative movement of the central columns and upper capitals is obtained (Fig. 12,a) which produces balancing axial and flexural forces in the adjacent ribs. Some real effects that are observed in these zones may also be correlated to such a movement of the capitals, like a more extended cracking in the ribs and diagonal cracks in the upper slab.

The nonexisting part of the structure was simulated by the hypothetic forces that it would have caused on the existing part. These forces were known through some labels that were visible in the remaining photographs of the original maquette. It was established that absolute funicular equilibrium would not have been obtained for the finished building either. In particular, the capitals tend to move in an opposite direction to that produced by the dead load of the Crypt level itself (Fig. 12,b). This suggests that the theoretic state of funicular equilibrium is only reached at an intermediate phase during the construction of the building.

To overcome the construction difficulties, Gaudi could have imagined a design in which a true funicular equilibrium was not entirely obtained either for the final configuration of the structure, or the construction at the crypt level. The disturbing effects due to imperfect equilibrium would thus be resisted thanks to the confinement action of the very stiff vertical elements. The perfect funicular equilibrium would have been reached at a peculiar intermediate stage of the construction process, being any previous or latter alteration of it counteracted by the enlarged capacity and stiffness given to the resisting vertical elements. This is just an speculative suggestion to explain how the architect could have accounted for the inherent difficulties of constructing a system laid-out through a funicular model.

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