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Studies of Gaudi's 'Cripta de la Colonia Güell'

Etudes de la 'Cripta de la Colonia Güell' de Gaudi

Studien zu Gaudi's 'Cripta de la Colonia Güell'

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SUMMARY

The Crypt of the Colonia Güell is the only part actually built of a construction envisaged by Gaudí and erected during the period 1908 to 1915. To assess the design of its unique structural system, Gaudí developed a tridimensional funicular model in which strings were used to represent actual brick masonry arches and oblique brick or stone columns. This paper describes a numerical analysis which was performed to study in detail the actual resisting mechanism under gravity loads for the built part of the structure, aiming to measure the alteration of the funicular equilibrium and relate it to the observed damage.

RÉSUMÉ

La Crypte de la Colonia Güell est en fait la seule partie existante d'une construction imaginée par Gaudí et construite entre de 1908 à 1915. Pour concevoir cette structure unique, Gaudí avait développé un modèle tridimensionnel des forces dans lequel des cordes étaient utilisés pour représenter les voûtes réelles en maçonnerie de briques et les colonnes obliques en briques ou en pierres. Cet article décrit une analyse numérique qui a été réalisée pour étudier en détail l'état actuel du mécanisme résistant sous les charges gravitaires de la partie construite de la structure, dans le but de mesurer le déséquilibre des forces et d'en tirer une relation avec les dommages observés.

ZUSAMMENFASSUNG

Die Krypta der Kolonie Güell ist der einzige wirklich errichtete Teil einer von Gaudí projektierten Kirche. 1908 begonnen, wurde ihr Bau 1915 eingestellt. Um ihr einzigartiges Tragsystem zu konzipieren, hatte Gaudí ein dreidimensionales Seilpolygon-Modell entwickelt, in dem Schnüre zur Darstellung des Kraftflusses in den Mauerwerksbögen und schiefen Ziegel- und Steinpfeilern verwendet wurden. Der Beitrag beschreibt eine numerische Analyse des tatsächlichen Lastabtrags des Eigengewichts im unvollendeten Bau, mit der die Abweichungen der Stützlinien bestimmt und mit beobachteten Schäden verglichen werden sollen.

1. THE CRYPT OF GAUDÍ

1.1 Description of the building

The crypt of the Colonia Güell is the only part actually built of what was to have been the parish church of the model village founded by Eusebi Güell in 1890. Gaudí was commissioned to design the parish church in 1894, when he was also working on the Casa Calvet, Bellesguard and the Expiatory Temple of the Sagrada Familia. The foundation stone of the church was laid in 1908, fourteen years after the commission, ten of which were spent on the preparation of the project. Gaudí abandoned the work in 1914, leaving the crypt and the portico finished.

The general form of the floor plan is oval, with a star-shaped outline, and it measures 26 m by 63 m. On the south facade there is a portico which signals the entrance to the crypt, and was intended as the access, via two flights of steps, to the church, located on the floor above. 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.

The interior of the crypt is in two parts, clearly differentiated as far as their structural conception is concerned; the rear part, containing the choir and the service areas, is covered by brickwork vaults which rest on metal T-section beams. The other part is the presbytery and chapel. The roof consists of bricks board (in Catalan and in the Catalan variety of Castillian, this type of slab is known as a *solera*), supported on brickwork ribs (a rib-shaped structural element formed of a flattened arch supporting a wall of the same thickness which fills in the void) supported by rowlock arches or resting directly on the supports whose longitudinal axis is inclined to a greater or lesser extent, with an inclination dictated by the funicular model which generates the shape of the building. (Fig. 1) Our study is limited to this latter space.

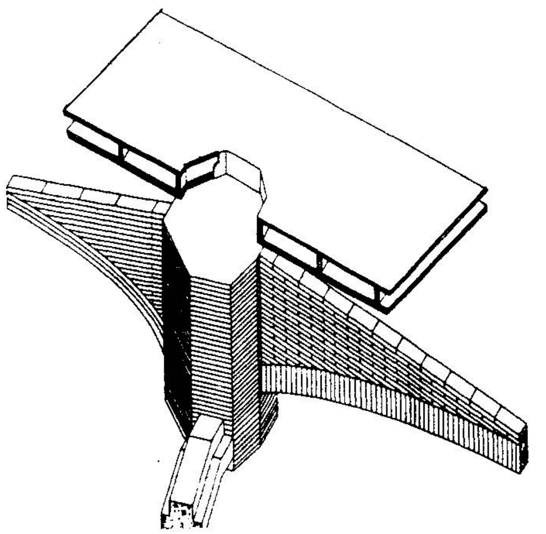

Fig. 1

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 ambulatory, made up of ten columns arranged in a double semi-circle around the nucleus. Columns and pillars support the main brick rowlock 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 – consist of a brick rowlock arch 15 cm thick, supporting a wall of the same thickness. The remaining ribs are walls 12 cm thick, but these are raised over brickwork arches three courses thick. The reticulum formed by the meeting of the ribs is flush at the same level and supports the *solera* mentioned above. 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.

The whole arrangement of columns, arches and ribs is the realisation of the funicular model which Gaudí built and studied over the ten years before work started on the building. More details in regard to historic or construction aspects may be found in[1].

1.2 The stereo-funicular model

It is known that the method used by Gaudí to approach the planning of the shape of the church was based on the properties of funicular polygons. The use of funicular lines as a system of determining intrinsically stable shapes had already been known for some time. Nonetheless, no major building had been erected on this principle; there is no doubt that the crypt is the first, with the peculiarity of being a set of funicular lines interwoven in the three spatial dimensions. The limitations of the graphical or numerical methods available to him obliged Gaudí to work out his stereo-funicular structure using a physical scale model.

But these are forms which, by virtue of the funicular device, reveal in their essential form the optimisation of the mechanics of their construction, with which Gaudí created shapes of overwhelming plastic expressiveness backed by a deep knowledge of the laws that govern the behaviour of the built fabric.

The only surviving documentation of the original model is a few photographs, most of them of the part which was not built. However, this lack may be in part made up for thanks to the initiative of a group of Dutch and German admirers of Gaudí's work who carried out the huge task of reconstructing the hanging model which, together with the publication which describes the lengthy and complex experience of its creation, is a very valuable contribution[2]. The correlation demonstrated by comparing photographs of the new model and that by Gaudí permits reasonable speculation about new images of the unbuilt church.

Examination of the model supplies data which greatly contribute to better understanding and knowledge of the existing building, such as, for example, the following point which has never been brought out and is doubtless of some importance. While the columns and the perimeter wall owe their inclination to the general funicular lines of the building as a whole, the same is not true of the two basalt columns close to the altar. The columns of the floor above were to have been essentially vertical. (Fig. 2) The inclination of those in the crypt was imposed by Gaudí for compositional reasons, and it has been achieved thanks to the thrust generated by the arches or ribs which would support the floor of the church and which were to divert the vertical loads towards the axes of the inclined columns. At all events, all this gives rise to a doubt: 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?

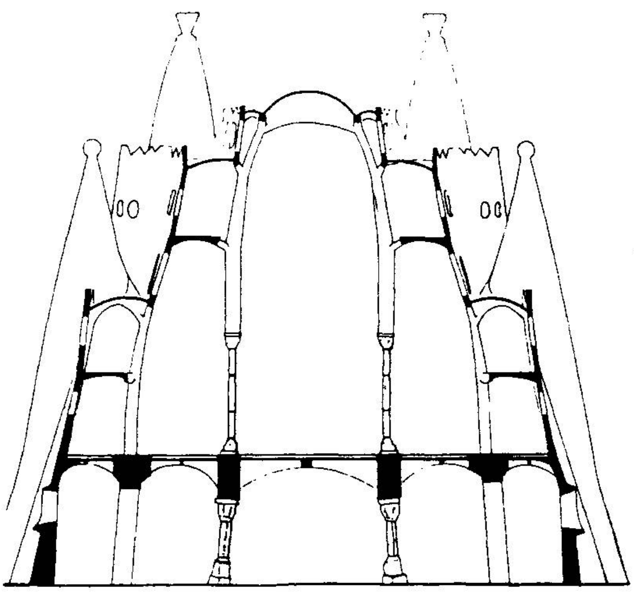

Fig. 2

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 nonetheless it is stable now, in its unfinished state. Graphic statics does not help us to analyse this problem.

However, one may still think that the structure behaves according to the funicular model, albeit 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 hypotheses about the behaviour of the building: the intricate pattern of cracks in the facing brick ceiling or *solera* which covers the central nave of the crypt, and those which affect several of the ribs and some of the arches.

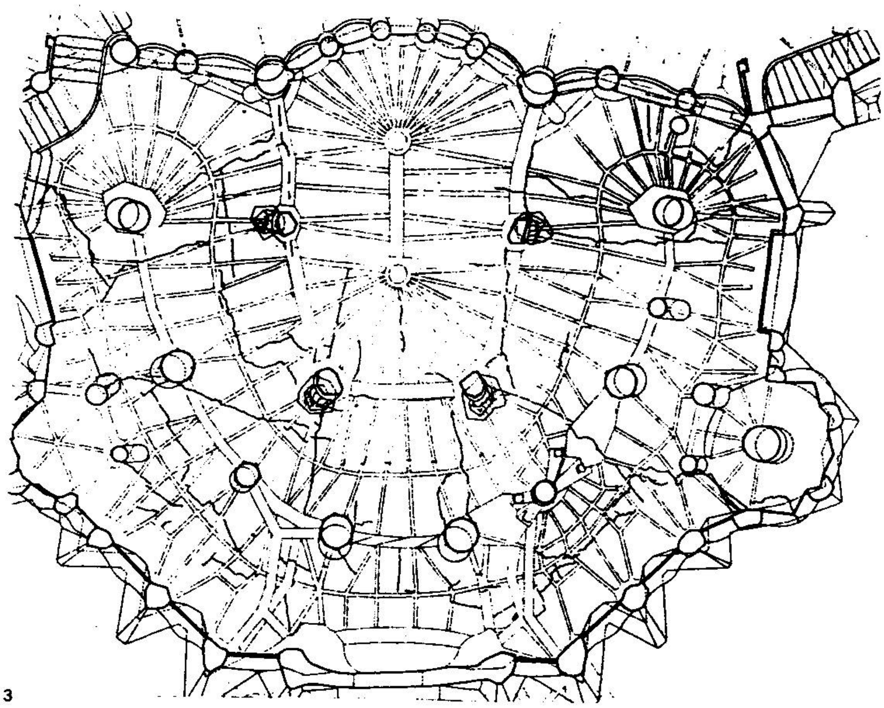

Fig. 3

Detailed analysis through direct observation and an exhaustive photographic survey of over 1 000 images has enabled us to determine the pattern of cracks we reproduce here, which is only an overall view amongst all those that were detected. (Fig. 3)

In fact, while the building has not collapsed, neither can we say it is undamaged; that is to say, structural damage has occurred which implies a distribution of forces other than that which was planned.

2. STUDIES

2.1 Numerical analyses performed

In order to reach a better understanding of the present state of equilibrium of the structure, a detailed numerical model was developed, in which the geometric complexity of the structure was accounted for by means of finite linear elements with curved centroidal axes, as well as arbitrary cross-sections, which made it possible to model the arches, ribs, diaphragms and columns incorporated into the existing structure. In addition, solid undeformable elements were introduced to simulate the massive capitals where columns, arches and ribs connect. The formulation adopted for the linear elements makes it possible to reproduce states of stress caused by combined axial, shear, bending and torsion forces, and thus to simulate possible modes of global equilibrium more complex than that of a funicular model, also taking into account the influence of the distribution of rigidity between structural elements. The used method of analysis was based on a Generalised Matrix Formulation (3).

2.2 Development of a detailed model

Using the technique described above, a detailed model of the structure was constructed from the information provided by the elevation, the *in situ* measurements and the photographic report. The available funicular model was also taken into account for a better understanding of the structuring of some hidden parts where ribs were connected to the perimeter wall. The

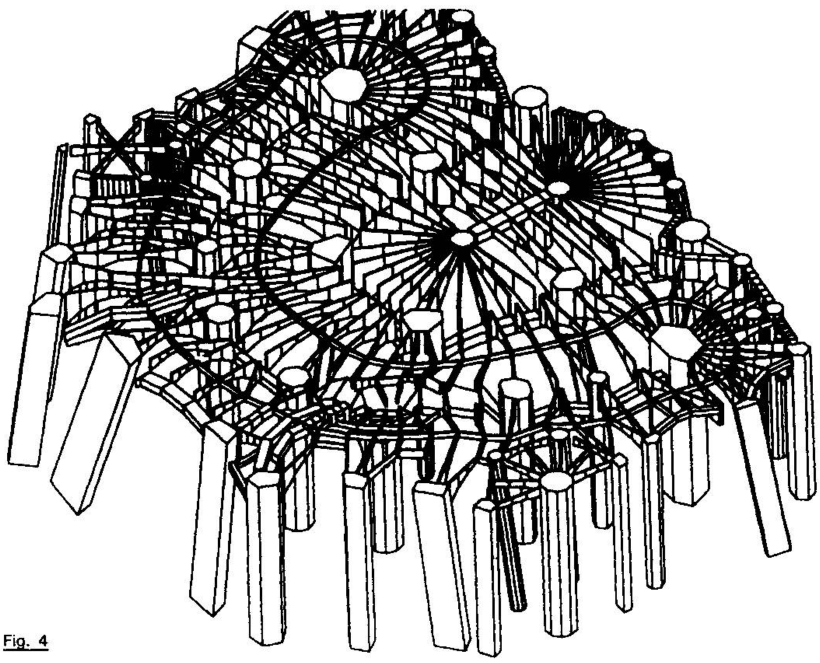

Fig. 4

result was the computer model represented in Fig. 4 and some preliminary analyses were carried out to discover its performance. The lead joints on the central columns at their junction with the pedestal and the capital were treated alternatively as completely fixed or rotationally free hinges.

2.3 Assessment of the present state of the structure

The first analysis consisted of a study of the existing part of the structure subjected to the vertical load produced by the weight of the skeletal system of ribs, arches and columns, as well as the weight of the upper slab, which rests on the first.

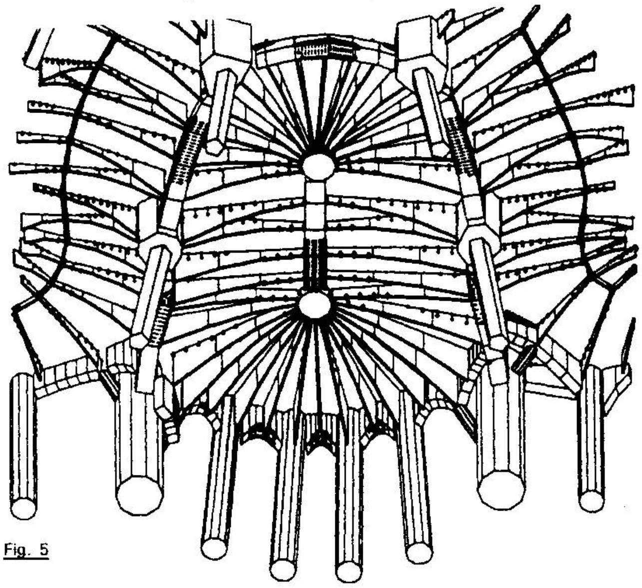

Fig. 5

The following conclusions were drawn:

A correlation was found between the zones where tensional stresses were concentrated and the cracks observed in the structure. All these cracks match the analytical prediction, which nevertheless showed many other potentially cracked zones which were apparently intact. 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.

According to the behaviour obtained, horizontal movements remain very small, showing the stability of the existing structure. The tensional stresses obtained in the different elements (Fig. 5) are mainly caused by their behaviour under vertical load and are hardly influenced by interacting forces due to global equilibrium. Thus, higher tension zones appear at the joints between ribs and capitals or arches and lower tension zones at the middle of the span of the ribs. Both types of tension zones have been correlated with existing cracks.

2.4 The rheological actions

But there are very significant radial cracks which cannot be explained by mechanical 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 lie between 1 and 7 to 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 constructional procedure which is not ordinarily used, and on which tests have not generally been carried out. However, the values could not be lower in view of the larger relative proportion of mortar in the section.

We now have to consider a point of considerable importance: the usual way of constructing these vaults is to treat the first skin, the *senzillat* in Catalan, with plaster, hence avoiding the need to use any auxiliary means of support, while its expansion compensates in part for the contraction of the other layers of limestone mortar. However, examination of the exposed layers of this material leads us to doubt that it is plaster. Diafractometric analysis revealed something unusual: the first skin is Portland cement.

The slow setting speed of this mortar made it necessary to locate battens, as can be seen from the marks left in the surface, to support the bricks while construction proceeded. The same tests showed that the two intermediate layers of mortar are also of Portland cement, although it was not possible to determine the proportions since a large enough sample was not available. The reason for this decision may lie in the desire to achieve greater strength in the structural element which was to support the congregation, and also so that the *solera* would be resistant to the elements until the whole complex construction which was to cover it had been finished.

If we take the longer dimension of 23 metres and consider that, although hard to determine precisely, the total of the cracks in this direction amounts to 3 millimetres, this leads us to believe that there has been a contraction of 2 or 3 tenths of a millimetre per metre, which in view of the mortars used is the least that could be expected.

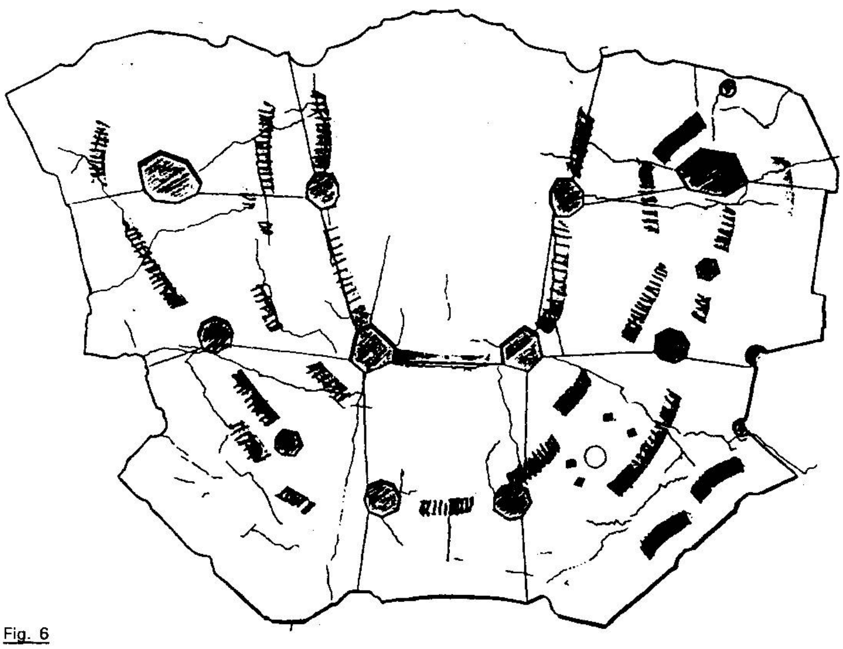

Fig. 6

The figure 6 is 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 suppose 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. There is a fairly considerable correlation between hypothesis and reality, and hence it seems we must inevitably conclude that the radial cracks are all due to contraction, while the cracks between the heads of the columns, the capitals, are due to a combination of contraction and the tension phenomena of the rib arches.

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 *solera* coincide.

The computer model together with hydraulic contraction theory allow us to define a model which adequately represents the real structure and supports the following conclusions.

3. CONCLUSIONS

3.1 The actual state

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 to the structure. While the combined effect of the tensions of mechanical and rheological origin – as well as possible compressions greater than the permissible level on some of the crushed bricks – have caused failures in the structure, namely the cracks in the *solera*, some ribs and some arches, the overall stability is more than assured, thanks to the inertia of the interior columns and the perimeter walls. That is, the horizontal structure has given way somewhat to the forces bearing on it, while the vertical structure has plenty of strength and stability in hand in spite of certain structural peculiarities or trangresions which might counter this.

The change to public use of the terrace above would mean an increase in the load supported by the ribs, and hence an intensification of the effects which can be observed or detected by computerised study: the generation of tensions in the key (lesser), the springer (to a greater extent) and the possible appearance of cracks.

Evidently it is dangerous to place further loads on the ribs which are visibly damaged, since their present state of equilibrium may be precarious, although there is the possibility of carrying out some sort of repair which would restore their ability to function as arches. The probability that there are imperceptible or potential cracks in itself makes it inadvisable to apply variable loads which would submit the structure to cycles of load and unload, since this would have the effect of creating new cracks and opening the existing ones.

Hence we can state that any hypothetical use of the terrace would have to avoid the direct application of loads on the *solera*. At all events, in view of their robustness, the columns will allow far higher load levels than those to which they are at present subjected, so that they could be used as the support of a new load-bearing structure. It must be borne in mind that the central columns, as discussed below, can only be loaded up to some 20 tonnes without producing desequilibrium in the opposite direction.

When lead joints are treated as perfect hinges, a significant movement of the central columns and upper capitals is obtained (Fig. 7) and produces balancing axial and flexural forces in the adjacent ribs. Some real effects observed in these zones may also be correlated to such a movement of the capitals, such as a more extended cracking in the ribs and the existence of diagonal cracks in the upper slab.

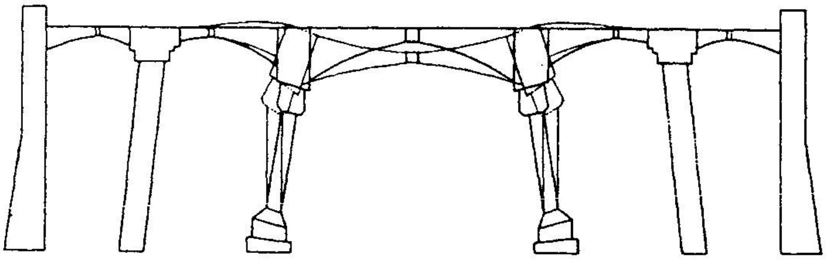

Fig. 7

Except in the zone close to the moving capitals, the distribution of forces obtained at the level of the arches and ribs remains similar to that of a funicular type of equilibrium, although the geometry does not correspond to that of the 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 overall structural system is not completed.

3.2 Analysis of the hypothetical complete structure

The unbuilt part of the structure was simulated by the hypothetical forces that it would have exercised on the existing part, and on the model. These forces were known from labels which can be seen in extant photographs of the original model.

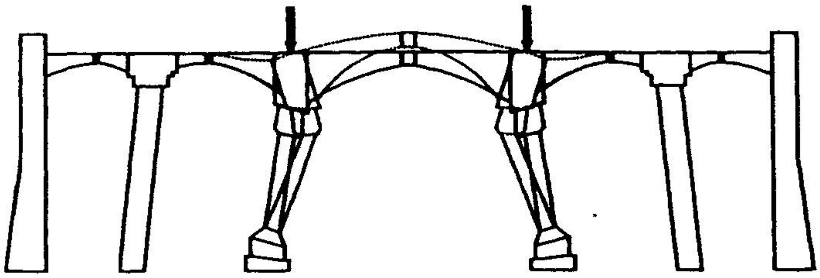

Fig. 8

It was established that absolute funicular equilibrium would not have been obtained for the finished building either. In particular, with the introduction of hinges and lead joints, the capitals tend to move in the opposite direction to that produced by the vertical load of the crypt level itself (Fig. 8). This suggests that the theoretical state of funicular equilibrium is only reached at an intermediate stage of the construction of the building.

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