Advanced Materials Research Vols. 133-134 (2010) pp 137-142
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doi:10.4028/www.scientific.net/AMR.133-134.137

Gothic Structural Theories Ca. 1930: the Contribution of Victor Sabouret

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Abstract: In the second half of the 19th century, the French architect Viollet-le-Duc published his *Dictionnaire raisonné de l'Architecture Française*. In this work he proposes, for the first time, a rational theory about gothic structures based on the existence of "active" and "passive" elements: vaults are made of passive webs supported by active ribs; pinnacles contribute, in an active way, to the stability of the buttresses; flying buttresses transfer the load from the vault, etc. Until 1900 Viollet-le-Duc's approach to the structural behaviour of gothic constructions was a dogma unanimously accepted by most architects, archaeologists and historians, but throughout the following two decades it became the object of harsh criticism. Discussion about the way gothic structures worked reached its climax at the end of the 1920's, when the engineer Victor Sabouret published his first article against Viollet-le-Duc's rationalist ideas, entitled *Les voûtes d'arêtes nervurées. Rôle simplement décoratif des nervures*. He specifically focused his discourse on the behaviour of vaults: on the decorative as opposed to structural or constructive function of the ribs. Although his arguments are mistaken and inaccurate in some aspects, he had an enormous influence over subsequent generations, and a large number of studies in the field were published throughout the years following this publication. Authors of such studies include Marcel Aubert, Henri Focillon and Henri Masson, whose publications revealed their disagreement with both theories, as well as Pol Abraham, who was in complete opposition to Viollet-le-Duc. In this paper, the Limit Analysis of the modern theory of masonry structures, formulated by J. Heyman in the 1960's, is used to evaluate the accuracy and suitability of Sabouret's criticisms to the rationalist theories.

Keywords: Rib, vault, sabouret, viollet-le-duc, limit analysis.

Introduction

The long tradition of studies in the field of gothic architecture experienced a change of direction in the mid-19th century. A great number of architects, archaeologists and historians began to show their interest in the technical and constructive aspects of medieval buildings. The structural behaviour of these constructions became the main topic of their research.

The French architect E. E. Viollet-le-Duc was one of the pioneers in using this new structural approach, and surely the most influential one. His rationalist theory of gothic construction, based on his knowledge of structural mechanics and his experience as a restorer, was first published around the 1840's in a series of articles in the *Annales Archéologiques* (Viollet-le-Duc 1844-1847). His purpose was to analyse the gothic structural behaviour from a novel perspective: from the point of view of the statics and the functionalism. In the next decade, his splendid compendium entitled *Dictionnaire raisonné de l'Architecture Française* came out (Viollet-le-Duc 1854-1868). In this masterpiece he gathered together all his rationalist ideas, repeating and developing some of those that had already been published before.

According to Viollet-le-Duc all the shapes in this kind of architecture served a logical and functional purpose. Starting from this premise, he develops the idea of the existence of active or supporting elements and passive or supported elements (webs, etc) in gothic structures. In the case of vaults, he declares that all the ribs comprise a stone skeleton that works as a permanent centering supporting the whole weight of the web and transferring the loads to the abutments (see Fig. 1).

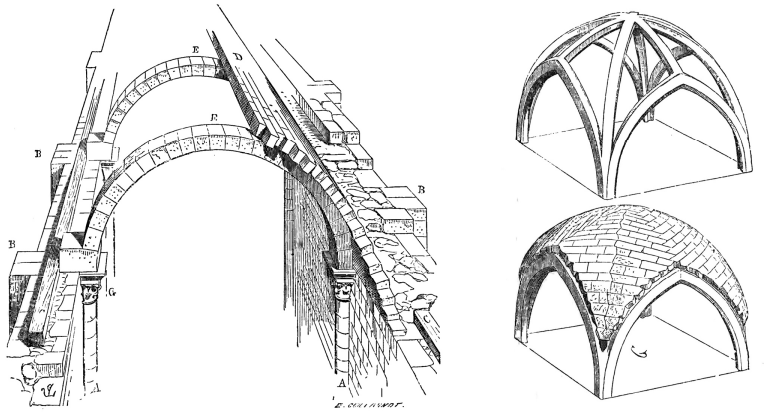


Figure 1*: Stone skeleton and webs in barrel and rib vault (Viollet-le-Duc 1854-1868)*

Supporters and Detractors in the Debate Regarding Gothic Structures

Throughout many years, Viollet-le-Duc's rationalist approach to gothic construction was unanimously accepted by most scholars in the field, not only in France but also in other countries. Among all his followers, Auguste Choisy was, probably, the most distinguished one. With his book *Histoire de l'architecture* (Choisy 1899), he contributed to the spreading and the consolidation of Viollet-le-Duc's ideas – ideas that he had carefully analysed and expanded.

The first critics of this new ideological current appeared almost fifty years after the rationalist architect's publications in the *Annales Archéologiques*, but only a year after his death. In 1880, Anthyme de Saint-Paul wrote a long critical essay, *Viollet-le-Duc et son système archéologique* (Sain-Paul 1880-1881), where he called into question the validity of the classical or rationalist reasoning. After the publication of this book, a large number of authors (Brutails, Enlart, Porter, Vaillant, etc.) showed their disagreement with Viollet-le-Duc's theories. They all thought that gothic buildings were not as logical or as rational as Viollet-le-Duc and his disciples had argued and they highlighted the importance of the decorative role in gothic architecture.

All these contributions led to a long and intense debate between those who supported the constructive and rational logic in medieval buildings and its detractors who denied any structural function in those constructions. During more than a hundred years, gothic structures were subjected to a meticulous analysis, and although the whole gothic architecture was the object of these studies, most of the discussions in this controversy were focused specifically on the behaviour of vaults.

In the 1920's and the 1930's, the debate was in its most brilliant period. After the First World War, Roger Gilman carried out an exhaustive study of the ruins of Reims and Soissons cathedrals in order to explain how these masonry constructions worked (Gilman 1920). This original approach, based on his observations of damaged constructions, provided him with new structural cases that were not very common in buildings. His ideas contrasted with Viollet-le-Duc's arguments, but they also agreed in some crucial aspects, like the role of ribs in vaults.

In 1928, the French engineer Victor Sabouret, whose theories are carefully studied in this paper, published a critical article against the rationalist principles. In this article, he focused on the behaviour of medieval vaults and he attributed a merely ornamental function to the ribs in barrel, groined and ribbed vaults (Sabouret 1928).

The most devastating attack to Viollet-le-Duc's ideas was due to the architect Pol Abraham (1934). His book, *Viollet-le-Duc et le rationalisme medieval*, is a savage criticism that contradicts all the arguments of the rationalist theory. According to Abraham, the classical premises are inaccurate, anachronistic, contradictory, and based on a priori ideas. From his point of view, the webs are self-supported elements and the ribs, which have no structural utility, are only decorative elements.

Throughout the 1930's, the discussion continued unabated (among Aubert, Masson, Focillon, etc.), until the outbreak of the Second World War interrupted the proliferation of studies in the field of

gothic structures. After the second half of the 20th century, scant interest on the subject consigned this hundred-year-old debate to oblivion.

Structural Behavior of Gothic Vaults: Victor Sabouret

Born in 1851 in Montluçon, Victor Sabouret was a distinguished engineer experienced in steel construction and an enthusiast of religious architecture. His work in masonry structures stands out as one of the first big criticisms to Viollet-le-Duc's rationalist ideas. Both his sound grounding in mechanics and his more than sixty years' experience in building bridges were the foundation of all his theories published in his articles *Les voûtes d'arête nervurées: rôle simplement décoratif des nervures* (1928) and *L'evolution de la voûte romane du milieu du XIe siècle au début du XIIe* (1934). In these documents Sabouret analyses the behaviour of vaults, paying special attention to the role of the ribs in these constructions.

According to the French engineer, the joints of a masonry construction play an essential role in its structural behaviour. On the one hand, settlement intensifies with the number of joints and their thickness; on the other, the resistance of the masonry depends on the resistance of the mortar used in the joints. Among all the characteristics of medieval mortars, its negligible tensile strength is the most important one: sliding can be avoided due to the adherence of the mortar and the force of friction between the mortar and the stone, but when tension appears, the mortars cannot support the stress and the masonry falls or breaks. Sabouret explains that the distribution of points of stress in a masonry structure is not uniform and does not depend on the orientation of the joints. This first approach to masonry constructions is the basis for his entire theory of medieval structures.

Sabouret's conception of vaults comes from his analysis of their cracking. When the abutments of a vault yield, i.e., when they lean or settle, the vault becomes distorted and cracked. These cracks are always located in those parts of the structure where the compression forces turn into tensile forces. Both in barrel and cross vaults, he describes three hinges (see Fig. 2 a): the first one on the intrados of the keystone and the other ones on the extrados at the level of the reins (forming an angle of 30º with the horizontal) roughly coinciding with half of the height of a semicircular vault and a little higher in a pointed vault. In this regard, Sabouret declared that the big decorative keystones can only increase the size of the crack on the top of the vault.

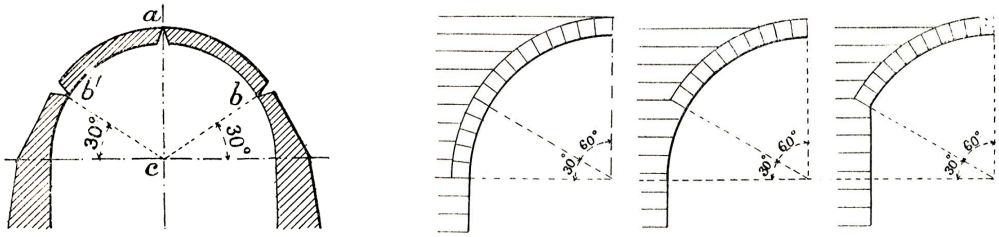


Figure 2: Hinges in vaults (a) and bonding in the tas-de-charge (b) (Sabouret 1928)

The brilliant engineer used this model to explain his own thesis about how vaults worked. From his point of view, the abutments do not end in the capitals but in the lateral hinges, thus, the part of the vault located under the reins works as if it belonged to the abutments (the bonding of the masonry in this part of the building is only important from an aesthetic point of view and not from a structural one, see Fig. 2 b). The rest of the vault constitutes the vault itself, a self-supported element that leans on those effective abutments working as a triarticulated arch. Longitudinal arches counteract each other in such a way that only a vertical load is transferred to the pillars and the walls under them can be replaced with large windows. This load also helps to equilibrate the thrusts developed by transverse and diagonal arches, which tend to lean the abutments.

This theory differs noticeably from the one set out by the rationalists, for whom vaults were basically made up of a self-supporting stone skeleton and independent webs. On the contrary, this approach agrees with Pol Abraham's ideas (Abraham, 1934) published six years after Sabouret's first article (Sabouret, 1928). Although Abraham began his investigation in 1923, based on Sabouret's

comments in his second article (Sabouret, 1935) it seems that he had not heard about Abraham's work until its publication in 1934. The influence of Abraham's thesis becomes completely evident in the second of Sabouret's two articles about vault's behaviour.

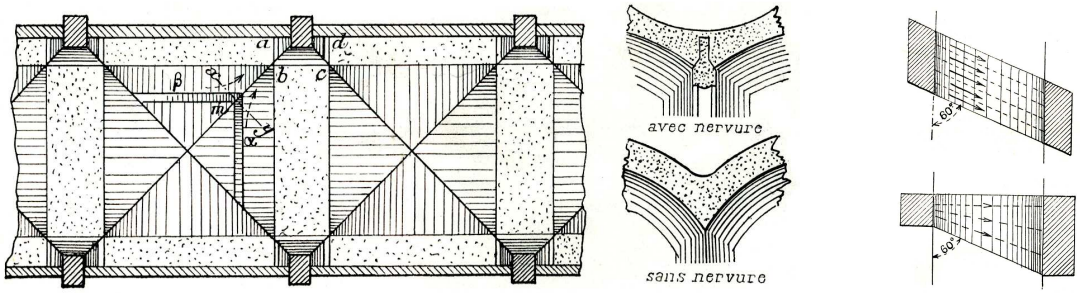


Figure 3: Structural behavior of vault and section of a groin (a); Maximum angle (b) (Sabouret 1928)

Victor Sabouret imagines that vaults work as if they were made of a juxtaposition of sliced arches through which the load is transferred (see Fig. 3 a). This assumption, exposed in both of his articles, requires that although the slicing does not necessarily have to be perpendicular to the abutments, the maximum angle must not be above 30º (see Fig. 3 b). In a cross vault, there are always two elementary arches converging in any point of the diagonal arch. The resultant of the thrusts of each pair of arches will be diffusely transferred through the groin to the abutments, regardless of the orientation of the joints and the bond, without sudden changes of direction along its path and using for that purpose as much area of web as it needs. In his second article, published only one year after Pol Abraham's book, Sabouret takes this topic up again, adding some nuances to his first explanations: the path followed by the thrusts is, as Abraham had already said, the line of maximum slope, that is, the track described by a marble rolling freely across the extrados of the vault (see Fig. 4).

Bearing in mind the principle that the thrusts are diffusely transferred, Sabouret asserts that the existence of a rib in a vault does not necessarily entail that those thrusts will pass through it. The ribs constitute only a small part of the whole section through which forces can be transferred and therefore their presence in a vault does not confer any significant structural advantage (see Fig. 3 a). This difference between the physical and the functional rib is essential in order to understand his ideas. According to him the influence of the ribs comes down to the part of the vault situated just over them, not expanding to the adjacent areas and, consequently, if the thickness of the web is such that there are no ribs, then it will also be sufficient in the area corresponding to the ribs.

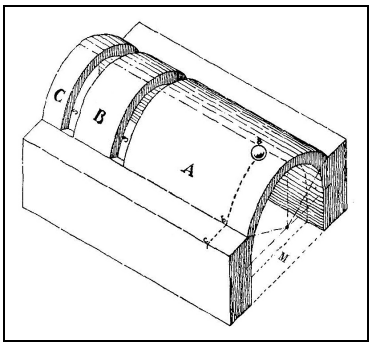
Sabouret questioned Viollet-le-Duc's structural role of the ribs on the vaults, asserting that they were only decorative elements. He found evidence of this both in the large number of vaults erected without arches (Vézelay shows good examples of considerably sized vaults without diagonal ribs) and in all those vaults that, as a result of the passage of time and wars, have lost their arch ribs without affecting the stability of the building (see Fig. 5).

Besides this structural uselessness, he also ruled out most constructive benefits: ribs do not improve resistance, do not facilitate construction (he admits that the existence of ribs simplifies centering during construction, but not enough to justify them) and can not be used as reinforcement of the vault (far from being a reinforcement, both transverse and longitudinal arches load the vault even more). He only saw certain constructive advantages of the diagonal ribs at the cutting of the groins and of the longitudinal arches at their role as "couvre-joints" between the wall and the vault.
Sabouret did not dismiss ribs because they did not fulfil a structural or constructive function. On the contrary, he suggested that their secondary role was perfectly legitimate and valid.

Analysis of Sabouret's Theories in the Framework of the Modern Theory of Masonry Structures

Sabouret's ideas as well as those of all who participated in this long debate concerning gothic structural behaviour were based on contemporary theories of arches and vaults. Viollet-le-Duc did not

use any structural analysis and his conception of masonry constructions is the result of his experience as an architect and a restorer of monuments. Some year later, Sabouret and Abraham applied the elastic theory to gothic structures (since the end of the 19th century and until the formulation of the theory of the limit analysis, the elastic approach was considered the most suitable for analysing structures). Today we know that none of the theories mentioned above is completely correct and appropriate when employed in gothic architecture.



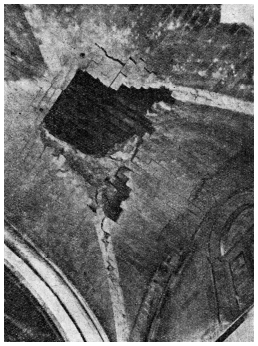


Figure 4*: Path followed by the thrusts (Abraham 1934) Figure* 5*: Spain (Torres Balbás 1945) Damages in Tortosa Cathedral,*

The modern theory of masonry structures was formulated by J. Heyman in 1966. In his article, *The stone skeleton*, he proposed to apply, in a rigorous way, the ideas of the limit analysis or plastic theory to analyse masonry structures. According to him, the application of this theory to masonry structures is only possible if the material has an infinite compressive strength, if it has no tensile strength and if a sliding failure cannot occur (assumptions that had already been exposed by Sabouret in 1928).

Unlike the elastic theory, limit analysis, developed by Baker in 1940, gives results that are hardly sensitive to small changes in the boundary conditions and the collapse load can be precisely determined in order to evaluate the safety of the structure. The potential of this new method lies in the safe theorem according to which if it is possible to find an internal stress state in equilibrium with the applied loads that satisfies the yield conditions, then the structure will be safe. Starting from the fact that there is not a unique calculable equilibrium state for structures, the great contribution of Heyman to this field is the corollary of this theorem, which states that the set of internal forces in equilibrium does not necessarily have to be the real one; it is enough that the equilibrium is viable for the structure to be safe. The plastic theory dispensed with the search for the real state of a structure, which had been desired by supporters of the elastic approach, and focused on the analysis on the way structures collapse (Heyman 1999).

The modern theory of masonry structures lays the foundation for a scientific debate on the behaviour of gothic structures, providing us with a theoretical framework from where we will be able to assess Sabouret's criticisms to Viollet-le-Duc's ideas. Focusing on his ideas about vaults' structural behaviour and the role of the ribs in vaults, we can propose that his arguments are not always correct if we interpret them in the field of the aforementioned theory, although this does not mean that they are necessary false.

His explanations for the way thrusts are transferred to the abutments, diffusively through the thickness of the masonry and following the line of maximum slope, show a logical structural behaviour that can certainly happen at a given moment and under certain boundary conditions. The mistake comes up when this state is expected to be the only way the vault can work and the real one.

On the whole, all structures move and become distorted when approaching an equilibrium state and only those in which this equilibrium cannot be found will collapse. The plastic theory states that if a structure is safe, it is because an equilibrium state has been found among the infinite equilibrium states that exist. Furthermore, the fact that it cannot be established whether the suggested state matches up with the real state, or is simply one of the possible states, lacks any importance. Only in some limit situations, for example, when cracks appear or when the thickness of the masonry is

extremely thin (in both cases the number of possible equilibrium solutions is considerably reduced), we can find an equilibrium solution that is close to the real state of the structure (see Fig. 6).

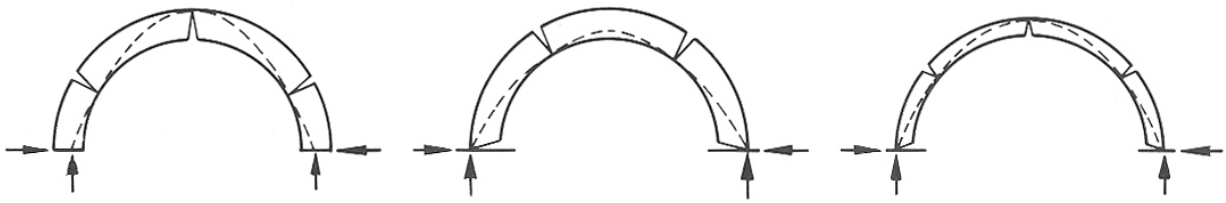


Figure 6: Possible equilibrium states (Heyman 1999)

Identical explanations can also be applied to Sabouret's ideas of the role of the ribs in the vaults. In the framework of the limit analysis, his hypothesis about the thrust not being necessarily transferred through the ribs and the ribs having an insignificant structural function can be one of the infinite possible solutions, but under no circumstances should it be understood as the only and real one. The same could be said of his assertion about the area of influence of the ribs coming down to the area placed just over them.

Conclusions

The critical reflection exposed in this paper comes up as independent research, with no contamination coming from the ideas and beliefs of the time period discussed herein. In this new context, although Sabouret's ideas are not completely wrong, they contain small nuances that prevent us from considering them absolutely right. Quite often, his arguments can be understood as a particular case of the modern theory of masonry structures, in the same way that the elastic theory, on which Sabouret's work is based, is a particular case of the limit analysis.

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