The Geometry and Construction of Byzantine vaults: the fundamental contribution of Auguste Choisy

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On fait la science avec des faits, comme on fait une maison avec des pierres: mais une accumulation de faits n’est pas plus une science qu’un tas de pierres n’est une maison.

Henri Poincaré

In 1883 Auguste Choisy published his book *L’art de bâtir chez les Byzantins*. In it he explained, for the first time, all the details of the geometry and construction of byzantine vaults. The main source was the direct study of the monuments, interpreting his observations in the light of traditional vaulting techniques. He is explicit about this: «ma seule ressource était d’interroger les monuments eux mêmes, ou mieux encore de rapprocher les uns des autres les faits anciens et les traditions contemporaines» (Choisy 1883, 3). Choisy focused on vaults, as he was convinced that the vault governs the whole architectural system: «Toutes les circonstances de la construction découlent ainsi de la nature de la voûte byzantine; et j’ai cru qu’il convenait de ranger les faits autour de cet élément fondamental du système» (4). The other fundamental principle is the economy of construction, as the vaults «. . . s’y subordonnent dans l’économie générale des édifices». The observations were made during a six month mission of the Administration des Ponts et Chaussées in 1875 (Mandoul 2008, 29). The following year he published a «Note sur la construction des voûtes sans cintrage pendant la période byzantine» (Choisy 1876), where he summarized the main results concerning the technique of vaulting without centring.

The book had an enormous impact on contemporary historians of Byzantine architecture. It was cited and praised for the new light it threw on constructive aspects, for the clarity and rigour of exposition, and for the superb plates. Eventually, his theories were incorporated into the manuals and histories of Byzantine architecture. The book by Choisy focus on «l’art de bâtir». The interest on the technical aspects of architecture almost disappeared after the First World War,
maybe due to the coming of modern architecture and the new materials (iron, steel and reinforced concrete). As a consequence, Choisy's works on «l'art de bâtir» were almost systematically ignored. The first specific study of Byzantine construction after the Second World Ward was written by Ward-Perkins (1958) and it has been considered, since then, the standard reference for Byzantine construction. Ward-Perkins ignored the work of Choisy making a passing criticism of his geometrical theories of Byzantine vaults. However, the detailed description of wall construction made by Ward-Perkins coincides pretty well with that of Choisy (7-13). He apparently was unaware that the whole theory of Byzantine vaulting without centring is Choisy's. Besides, he attributes to Giovanonni the detailed description of the use of brick ribs in vault construction. In all, it appears that Ward-Perkins did not read Choisy's book on Byzantine construction carefully nor was familiar with the history of vault construction. The consequence was that subsequent authors didn't take seriously Choisy's work or simply ignored it. Sanpaolesi (1971) in a dissertation with the suggestive title «Strutture a cupola autoportanti» simply ignores him. To Mango (1975), author of one of the standard manuals on Byzantine architecture, Choisy is superseded; Krautheimer (1984) did not consider Choisy when discussing, summarily, the vaulting problems. Robert Ousterhout, author of a book on the Master Builders of Byzantium (1998) considers Choisy «outdated», being «more than a century old». Even in detailed archeological studies of vaulted structures his work is ignored (Deichmann 1979). There are some exceptions in specialised studies on vault construction: Besenval (1984), Cejka (1978) and Storz (1994).

It must be said from the beginning that Choisy's *L'art de bâtir chez les Byzantins* is still the best source for anyone interested in understanding the geometry, construction and structural behaviour of Byzantine vaulted buildings. In what follows, we will try to demonstrate that this assertion is true.

**A theory of Byzantine vaulting**

The construction of vaults was one of the main aspects of Byzantine architecture, indeed of historical masonry architecture. There are three aspects to be considered, which are deeply interconnected: geometry, construction and stability. The architect or mason must have in mind a shape and thickness of the vault he is going to build. He also must have an idea of the process of building, including the material, the sequence of construction, the use of falsework, etc. Finally, he must, from the beginning, have the conviction that the vault is not going to collapse. These ideas form a more or less organised corpus, a system of practical knowledge, in the mind of the builder: he knows what could or couldn't be constructed, and what will be the price for changing this or that aspect of the general design.
A standing vault does not give much information about the processes involved in its design and construction. The construction historian, the architectural historian or the archeologist, trying to understand this must work backwards, trying to imagine the train of thought or, at least, the procedures employed in the construction of the vault. It is not a matter of a simple accumulation of information: a measured recollection of all the data concerning some kind of vaults (geometry, material, historical data, etc.) will not authomatically lead to a hypothesis of how these vaults were designed and constructed. This is, indeed, the problem. The archeological knowledge of the historical buildings has grown enormously in the last one hundred years. However, the theories, the knowledge needed to understand and relate these data has diminished almost in the same proportion. The teaching of masonry vault construction has disappeared from universities and the architects and engineers themselves are unable to understand the construction methods; the same occurs with archaeologists.

It is in this context that the importance of the work of Choisy emerges. Choisy gave rational explanations of the possible procedures to be followed to design and build the Byzantine vaults. As a rational system, it can be criticized, modified or improved; however, without a theoretical frame it is not possible to even think about the problems (cf. Poincaré’s words at the start).

Vault construction without centring

From the beginning, Choisy saw in the economy of centrings one of the central aspects of vault construction. In his study of Roman construction the brick arches («armatures») embedded in the concrete were placed to diminish the expense of timber for the rigid centrings. In Byzantium, he went a step forward and considered the possibility of finding a whole system of construction without centring. Simona Talenti has discovered that Choisy had this idea in mind before starting his mission: «L’idée de supprimer les installations auxiliaires ne se manifestait chez les Romains que comme une tendance, elle s’est définitivement réalisée chez les Byzants: je me crois même autorisé à affirmer que la plupart de leurs voûtes ont été construites sans cintrage» (Talenti 2009). Is there any other way to initiate a research than to have a work hypothesis? Of course, Choisy must have seen the drawings of Place (1867) of the sewage in Khorsabad, with its pitched arches, or he may have received or found information in the books of travelers through the Near East, but, nonetheless, his deep insight of the problem. Is impressive Perrot and Chipiez (1884, 172) were well aware of the importance of Choisy’s theory and cite him.

The essential aspect of building a barrel vault without centring is the so-called «pitched brick» technique. It entails, first of all building a wall; on the surface of
this wall the mason draws the profile of the vault with mortar (or clay); then, the first bricks are set flat against the wall and they are position thanks to the adherence of the mortar. When all the bricks of an arch are set, the arch is stable and may serve as centring for the next slice. The procedure, we know now, can be traced back to the origins of arch construction in the 3rd millenium B.C. (Besenval 1984, El-Naggar 1999) and is still in use in some parts of North Africa and the Near East, Figure 1 (a). But circa 1850, archaeologists were struggling to interpret the meaning of the «stripes» of bricks which may be seen in some vaults of the Late Roman Empire in the East, Figure 1 (b). (The technique is used today in some regions of North Africa and the Near East, Figure 2, and is well known for those working on earth construction.) However in the second half of the 19th Century, it was Choisy who first gave an answer to this curious disposition of pitched bricks.

With his usual modesty, Choisy (1876, 440) attributed the idea to a personal communication of the consul in Damas. He then described the construction of an experimental vault («voûte d’essai»), which he used to test the procedure himself. (The experience is not cited in his book of 1883.) For its interest, we quote the description in full:

La voûte d’essai que j’ai construite est un berceau en plein cintre de 3.40 m de diamètre sur 0.11 m d’épaisseur. Les matériaux sont des briques de 0.055 m, sur 0.11 et

Figure 1
Pitched brick vaults: (a) Tomb in Assur, Tomb 64, Neo-Assyrian Period (Besenval 1984); (b) Basilica of Aspendos. Second half of the 3rd Cent. (Ward-Perkins 1958)
0.22. Je les ai fait poser par tranches inclinées par rapport à la verticale d’une dizaine de degrés au plus. La conicité des tranches est à peine sensible. Enfin, pour rendre l’expérience plus concluante, j’ai remplacé le mortier par de la terre légèrement argileuse, sans y incorporer la moindre parcelle de chaux. Les circonstances étaient aussi défavorables que possible, et pourtant la voûte a parfaitement réussi. (Choisy 1876, 441)

In the book of 1883 he described in detail all the possible variations of the procedure, Figure 3: with vertical slices, with plane leaning slices, with curved slices (as in Fig. 1 (a)), and, eventually, with conical joints. Choisy fully discusses the advantages of every disposition and cites monuments where he has seen them. Of course, the method implies the construction of a wall or thick arch at one of the ends of the vault. If two walls are built, then the vault could be built from the two ends, meeting at the middle. The gap left is filled without difficulty.

The radial joint procedure may be sucessfully combined with advantage with the pitched brick technique: the first rows of bricks are built with radial joints.
without any centring and, then, the upper part is closed in turn using the pitched technique. In Figure 1 (b) there is an example of the 3rd Century. The Byzantine architects often used this rational and economical procedure. In Figure 5 (a) there is an explanation of possible combinations; Fig. 5 (b) show an axonometrical view of the a vault of the Church of the Holy Apostles in Thessaloniki. In Figs. 6 and 7 the axonometries of Choisy are compared with photographs of actual buildings to show the degree of detail and ingenuity of Choisy’s analytical drawings.

There is no space here even to mention the number of cases studied by Choisy in which the pitched brick procedure proved its versatility, each one with a reference to a certain monument. We will show two cases where the solution in stone
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Figure 4
Construction of vaults from the two ends: (a) explanatory diagrams (Choisy 1883); (b) substructure of the apsed hall of the Palace of Byzantine Emperors (Ward-Perkins 1958)

Figure 5
Combination of radial and pitched bricks: (a) possible combinations; (b) vault in the Church of the Holy Apostles in Thessaloniki.
or with radial joints would have been of enormous complexity; the drawings make evident the facility of applying the same procedure to conic or spiral vaults, Figure 8.
Domes

That domes could be built without centring, constructing successive rings, was well known to any architect and engineer of the 19th Century. Choisy focused in the particularities of Byzantine domes. He observed that the surface joints of the rings, instead of being cones with the vertex in the centre of the sphere (considering as a typical case a semi-spherical dome), had different angles, as shown in Figure 9 (a). He justifies this by the great inclinations of the joints in the upper parts of the dome. This may be questioned in relation with the inclination observed in the barrel vaults, and maybe the true reason was the simplicity and speed of construction. Anyway, Choisy states that he has always observed this tendency and that in many cases the direction of the cone generatrixes cut the

Figure 8
Complex problems solved by the pitched brick technique (Choisy 1883): (a) conic vault in the walls of Nicaea; (b) the vault of an spiral stair in a tower of the Pantocrator in Mount Athos.
Figure 9
Inclination of the conical joints of a dome (Choisy 1883): (a) explanation; (b) possible geometrical rule

Figure 10
Observation of the inclination of the joints (Choisy 1883): (a), (b) St. George in Tessaloniciki; (c) ruined vault in the fortifications of Constantinople; (d) pumpkin dome in the Chora, Istanbul
plane of the impost at the springings of the dome, Figure 9 (b). In fact, this is his supposition and he tested it observing real buildings.

He cites three cases: the dome of St. George in Tessaloniki, a ruined vault of the fortifications of Constantinople and a pumpkin dome under restoration. In the case of St. George, he made a detailed drawing showing the difference between the usual central cone, the direction following the above explained rule and the actual directions (Fig. 10 (a)), where the actual joints are represented the inside with a continuous line, to be compared with the dotted line of the theoretical inclination. The radial joints are represented on the outside. Inspecting his own analytical perspective of the building, it is evident that he must have seen them from the upper windows (Fig. 10 (b)). In the case of the ruined dome, it was the partial destruction which allowed him to inspect with care the internal structure of the vault (Fig. 10 (c)) and to verify the almost complete coincidence with the rule. The pumpkin dome of the Chora in Istanbul was under restoration and could be inspected in situ by Choisy.

Figure 11
Use of the pitched and radial techique in building apsidal domes: (a) examples gathered by Choisy (1883); (b) Saint Aberkios at Kursunlu (Ousterhout 1999) (c) Saint John of Troullo in Istanbul (Mathews 1976)
Choisy then explains the possible procedure to survey this inclination (Fig. 11 (a)). He then discusses the problem of closing the dome where the joints become almost (see Fig. 9 (a) above) and formulates another hypothesis: why not avoiding the problem continuing the dome with a conical shape? This is the shape of many islamic domes and Choisy considers that this constructive problem may be an explanation, Figure 11 (b).

Choisy studied also the case of the semi-domes. He analyses the great apsidal domes of Hagia Sophia, but also the small apsidal domes which were so common in Byzantine architecture. Again, he is interested in the process of construction and in the variations of the pitched brick technique which can be found in the small apsidal domes. All his drawings referred to actual buildings.

**Groined vaults**

The Byzantine architects solved in a revolutionary way the problem of the groined vault: the curve of intersection of the two barrels. If the two barrels are equal cylinders, then, the curve is an ellipse, an inconvenient shape for builders. But in the more general case of two different barrels, the curve is not even a plane curve, as was discussed already by Willis (1835), Figure 12 (a). Choisy (1873) examined the different strategies used by the Roman architects to avoid or diminish the problem. The solution was to invert the problem: not to obtain the intersection of two geometrically defined barrels, but to define beforehand this curve of intersection and the perimetral arches, and, then, to define the web surface. This was, of course, the method of the Medieval architects, but some centuries before the Byzantine architects have adopted the procedure; the only difference is that they did not reinforce the groins. However, from a strictly geometrical point of view, the approach is the same.

That the groins are plane curves in most cases can easily be seen by simple inspection. Choisy realized that this was the clue to decipher the strange shapes of byzantine vaults. The second step was almost obvious: adopting a circular profile for the intersection. Another aspect should be taken into account, the domical form of the Byzantine groined vaults. As can be easily seen in Figure 12 (b), once the architect or mason is free to choose the profile of the linear arches defining the vault, great number of solutions is possible. However the problem of the shape of the webs between the arches still remained.

Choisy supposed a simple surface of revolution generated by the diagonal groins turning around a horizontal axis at the level of the springings. The resulting surface has a peculiarity: it presents an inflexion on the curvature near the wall (Fig. 13 (a)). This afforded a way to check the validity of the hypothesis. In any case, the general form of the vault, deduced theoretically from this principle,
Figure 12
Curve of the groins: (a) Two unequal barrel vaults (Willis 1835); (b) Byzantine geometry (Choisy 1883)

Figure 13
Geometry of Byzantine vaults after Choisy (1883): (a) shape of the surface of revolution; (b) contour lines; (c) practical method of tracing the elementary arches
agreed pretty well with the Byzantine vaults, as is evident from the contour lines of Figure 13 (b). Choisy even discussed a simple method to draw the surface in the air with the aid of stick and rods, Fig. 13 (c). Choisy claimed that this inflection existed and was visible in the vaults of some cisterns and, in particular, at the narthex in Hagia Sophia, Figure 14 (a). In the photograph of Figure 14 (b) the inflexion appears to exist. Choisy has been criticised many times by the apparently complex geometry involved: Lethaby (1894), Ward-Perkins (1958) and many others. On the other hand Forchheimer and Strzygowski (1893) said to have observed it. Only a detailed survey (which nowadays entails no difficulties with the new laser stations) of a large number of vaults can dilucidate the problem.

In any case, what is important is the reasonable supposition that to build vaults of some size (such as the vaults in Hagia Eirene or Hagia Sophia) with a certain regularity, some kind of method to control the geometry must be used. This is obvious to any mason and it should also be to construction historians and archeologists interpreting vault geometries. The method proposed by Choisy is simple and can be implemented without special problems. This does not mean that it is «true». Probably we will never know the actual method employed.
However, Choisy remarks, at the end of the chapter on groined vaults:

Au surplus, il serait illusoire d'attribuer à toutes les voûtes byzantines un tracé géométrique rigoureusement défini, et dans plus d'un cas l'irrégularité de forme que présentent les panneaux des voûtes montre que les Byzantins se sont contentés d'un cimbelot pour tracer l'arêtier, se fiant pour régler la courbure des surfaces. . . (57)

Conclusions

We have seen a brief review of some of the most important contributions to our knowledge of Byzantine vault construction made by Choisy. The present author considers that, at least, this review would encourage some students, practitioners or scholars to read Choisy. It is not easy. His laconic style, his definite blunt assertions, the absence of explanations, made the modern reader uncomfortable. However, if the reader is able to jump over this superficial inconvenients he will find a gold mine of information and inspiration.

Notes

1. As the references to Choisy's book will be numerous in what follows a number between parentheses will indicate the page in L'art de bâtir chez les Byzants. When no page number is specified after a quotation, the quotation is in the same page as the previous one.
2. In fact, Choisy saw his work on Byzantine construction as a continuation of his studies on Roman construction (Choisy 1873). This is evident from the text, but for an explicit reference, see Choisy's letter quoted in the contribution of Simona Talenti, «De Viollet-le-Duc à Choisy: les historiens de l’architecture français face à Byzance» in this book.
3. See, for example, for the construction of the Byzantine churches: Lethaby and Swainson (1894), Van Millingen (1912 ), Ebersolt and Thiers (1913) and George (1913).
4. See Diehl (1910), Benoit (1912), Wulff (1914).

Reference list


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