Masonry vaults in Genoa: From historical and archaeological analyses to scientific interpretation of the rules for their construction

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In the course of successive investigations conducted by the authors, much data relative to the construction of masonry vaults was collected, particularly with regard to the city of Genoa in the modern era (sixteenth through eighteenth centuries). The sources of information utilised were two: the so-called «material source», comprising the structures that are preserved and can be inspected in one way or another; the «written source», comprising the documents in archives. In the course of this and other research, it was possible to observe how a systematic and careful comparison of the data gathered from two sources permitted us to better understand and interpret the data itself.

With regard to the material source, 120 vaulted structures were analysed. These analyses, which we define as archaeology because they were conducted according to the principles and methods of building archaeology, took into account the following aspects: general characteristics of the structure and its dating (morphological and typological analysis, stratigraphic analysis, chronotypological analysis of individual architectonic elements); materials utilised and their dating where possible (archaeometry of the mortar, mensiochronology of the bricks); the construction techniques adopted (general technological analysis, analysis of the masonry technique).

With regards to the written source, we availed ourselves of a digital database begun at the end of the 1980s that gathers more than 700 notary contracts concerning the building trade. For the purposes of research of vaulted structures, of particular interest were the documents of construction describing verbally, sometimes in more and sometimes in less detail, the work to be executed, whether in the case of new construction, restoration or maintenance of existing structure.

Given the differences in nature between the two sources utilised, the information that they provided was in part similar and directly comparable. Many times they completed and added substance to each other reciprocally. Sometimes they indicated the necessity for new research to fill gaps in their respective areas of applicability.

**Genoese Vaults of the Modern Epoch**

**Geometric form**

The most frequent typologies turned out to be those of barrel vaults, cross vaults, pavilion vaults and barrel vaults with pavilion vaults at their ends (which frequently had lunette vaults all around the perimeter).

**Material form**

The most frequently used material (in about 90% of the cases) is brick. Comparing vaulted structures to
other, coeval, masonry structures, several significant differences were noted: 1) in vaults, within the same structure, there were very frequently two kinds of bricks used, wall bricks and brick pavers, while in walls this combination was much less frequent; 2) the bricks used in vaults were characterized by a much greater dimensional homogeneity than that found in walls. This fact indicates the accurate selection and verification of the quality of the product undertaken by the builders at the time the material was acquired; 3) in vaults, contrary to what happens in walls, there is a sporadic use of recycled brick; 4) with respect to walls, it is possible to note a more frequent use of bricks that are very well fired (the so-called ferrioli), and vice versa, the scant presence of bricks that are not very well fired (these, when present, are mostly concentrated in the area at the centre of the vault).

**Thickness**

The thickness of masonry vaults in residential buildings, extracted from documentary information and verified by data gathered in the field, is generally a half-palm (approximately 12.5 cm), a dimension corresponding to the width of the brick. In the zone of the imposts, however, the thickness can double. Further, continuous or interrupted ribbing at the extrados is often provided (formerly called ghiane in Genoa), in correspondence to which the resisting structure doubles its thickness.

**Buttressing and infill**

Both the documents and the analyses of existing structures testify to the use of brick or stone buttressing set with mortar (the so-called masici) to stabilise the vault. An analogous role was played by the infill with rubble. In the case of small- and medium-sized vaults, rubble completely filled the spaces above the vault and, appropriately levelled, provided the setting bed for the pavement above. In the case of larger vaults (in churches and in the great halls of palaces and villas), the excessive load of a complete infill was avoided by means of structural solutions (small walls or vaults) or, where possible, allowing the top of the vault to emerge into the space above (usually attics or the spaces under the eaves).

**Chains**

The archaeological analysis of existing structures has verified the use of metal chains that are visible in the intrados of only 19% of the cases examined. Further, the presence of chains has been verified in the extrados of another 15% of structures. It is probable that, if not in all then in a great part of the remaining vaults, there is some form of hidden concatenation (within the precinct walls or in the extrados), in accordance with what is found in the documents. Even though the use of chains was not considered indispensable by builders in the past, in the contracts the placement of some kind of chain is often explicitly provided for, whether simple or furnished with bracci (literally, «arms» or oblique branches), sometimes arranged according to a kind of frame.

**A CASE STUDY: THE VAULT OF SANTA MARIA DELLE GRAZIE**

Among all the vaults studied, of extreme interest was the barrel vault with lunettes and pavilion vaults at its ends, Figure 1, that is found in the former convent of Santa Maria delle Grazie la Nuova. The convent was built starting in the fifteenth century on a site on which there had already been intense building in the Middle Ages. Between 1385 and 1460 the nuns proceeded to acquire various existing houses, with the aim of building «a church and convent with a cemetery and bell» dedicated to the Madonna delle Grazie (Boato 1997). A substantial part of the medieval walls was embedded in this new construction. They are still visible in part on the south side of the church. In the almost four centuries that passed between the first settlement of the nuns and the closing of the convent following the Napoleonic disposition in 1810, the complex was the object of continual construction campaigns, sometimes quite extensive.

In particular we know of a significant restructuring begun in 1623 (Costa 1934 gennaio: 3–5). In that year the nuns presented their request to Pope Gregory XV to be granted the funds required to enlarge the complex to make it adequate for the use of a religious
community that had by then grown to more than a hundred people. In the memos they set forth the necessity of amplifying the refectory and the work places, to increase the number of living cells and to enlarge the small ecclesia interior, then no larger than forty palms and not wider than fifteen palms (9.19 meters by 3.72 meters), to the more decorous fifty-four palms in length by thirty palms in width (13.38 meters by 7.43 meters).

Almost certainly, the result of this campaign is recognisable in the ample space to the north of the church, the end wall of which is richly decorated with stuccoes and which is covered by the vault that is the object of our analysis. The dimensions of this space (about 15.0 meters by 7.10 meters) are not in fact very different from those envisioned at the time, thus a space of dimensions that correspond to those of the previous «interior» church can be obtained by projecting onto the ground plane the structure of the walls above, which on the upper floors delimit the spaces that have characteristics that are more archaic than those of the lower hall.8

It is in fact the presence of walls of notable thickness and height bearing on the vault both longitudinally and transversally, together with the hypothesis that the realisation of the vault took place during a daring operation of centering, demolition and underpinning, that suggested the idea of a study of this structure. It symbolises all that the mastery of Genoa at that time could realise, thanks solely to the knowledgeable application of the construction methods conventionally used.

Even at first glance one notes an exceptional abundance of chains that tie in the vault transversally slightly above the level of the impost: there are in fact ten, placed in pairs in correspondence to every corbel. In addition this already remarkable system of concatenation, thanks to the degradation of the plaster, it is possible to see the presence of other.
hidden, chains that intersect the vault at the intrados, in correspondence with the apex and on its sides. This is a «slinging chain» system, usually employed as an alternate rather than in union with chains at the intrados. The anomalous adoption of a double system of concatenation is undoubtedly motivated by the exceptional nature of the context. As already noted, a wall some 75 cm thick and originally at least 6.5 meters high rests right along the apex of the vault, Figure 2. Two other lengths of wall of notable weight (one about 85 cm thick, the other 50) apply force on the vault in a transversal direction. The existence of such a load must weighed on the minds of the builders as well as on the vault, urging them not to stint in taking precaution. There is no doubt, in fact, that the whole system of chains was conceived and set in place at the same time that the vault was constructed. The proof of this lies in the fact that the upper chain, the lower chain and the diagonal branch are fixed by a single long anchor element.9

INVESTIGATION INTO THE CONSTRUCTION PHASE

Beginning in 1994 the edifice in question was subjected to a careful restoration, still in progress today. This has permitted the inspection and survey of parts that would otherwise have been hidden, and has also permitted the carrying out of several studies aimed at comprehending the construction system adopted for the vault.

The extrados of the vault is covered with rubble.10 Some excavations have allowed us to see that the extrados is ribbed by means of a system of transverse arches of widths that vary from about 1.0 to 1.5 metres, with a spacing between them of 1.05 to 1.45 metres. Such variations in dimension are surely related to the presence of the walls above, Figure 3 and 4. The arches have a thickness at their centre of two brick headers, equal to about 25 cm. The bricks of the arches do not appear to have ever been keyed into those of the vault below, the thickness of which is equal, at the vault’s centre, to 27.5 cm. However, one link between the two structures is shown by the presence of numerous large slabs of slate, which, in all probability, regarded the entire thickness of the vaulted structure.

In correspondence with the longitudinal wall, the head of the pavilion placed at the western end of the vault is likewise ribbed by a climbing arch on the extrados, which on one side has its impost in the perimeter wall and on the other is keyed into the side of the transversal arch. The thickness at the centre of the climbing arch is also equal to two brick headers, while it increases as it nears the impost.

Between rib and rib, in correspondence with the longitudinal wall, have been built very shallow arches, two brick headers thick, which have the function of counter-bracing the ribs and the transfer of the loads of the part of the wall above, Figure 5. The transversal arches are fitted with siding of brick and stone with lime mortar, the summit of which is at the same height as the chains of the extrados, Figure 6. Thus the part of the chain that
Masonry vaults in Genoa

Figure 4
Axonometric reconstruction of the vault structure

Figure 5
Extrados vault. Detail of the binding between a transversal arch and a little longitudinal arch that binds together the transverse arches

Figure 6
Extrados of the vault. The following elements may be recognized: the transversal arch, the extrados chains, the climbing arch at the end of the vault

Comparing the position of the transversal arches, reconstructed point by point thanks to the investigations performed on the extrados, with that of the chains that are visible on the intrados, it has been possible to verify, as was expected, a good correspondence between the dimensions: the five pairs of upper and lower chains therefore contain the thrust of the vault precisely in correspondence with the arches, which constitute in all senses therefore the principle load-bearing construction system.

Characteristics, Preparation and Setting of the Materials and the Elements of Construction

Observing this structure raises the question of whether the same investigation that informed the
whole process of design and construction of the project finds a correspondence in the choice of materials and the setting in place of the elements. The answer is affirmative: in S. Maria delle Grazie the careful selection of the materials is associated with their accurate use. Slight anomalies appear to have been dictated more by the necessity of adaptation to pre-existing conditions than to negligence on the part of the builders. An analysis of the materials employed gives rise to the idea that there was a careful selection process. The homogeneity of the bricks, for instance, is superior to what can be observed in other similar structures of the same period; the elements in stone that are used appear to be all of optimum quality. The mortar causes some perplexity: it contains some lime gravel and doesn't have any particular qualities of cohesion or adhesion. The system of underpinning and its relative construction in parts requires an accurate operation that must be executed by able master craftsmen: the analysis of this structure has revealed an elevated degree of competence on the part of those who executed the work.

The bricks

In terms of dimension, colour, and the characteristic of their mixture, the bricks used in the vault, the transversal arches and the connecting arches are very homogenous. These could be those which in the documents are called *ferroni*. Very rarely, and only in the supports, are there bricks that are recycled. Relatively scarce, with respect to the construction norms adopted, is the use of brick pavers.

In the vaults the bricks are arranged prevalently head to head, and rarely side by side. Of particular interest is the information regarding the frequency and the variation with which these cases are present: in the centre of the area comprised between the two chains are 29% of the bricks arranged side by side; this figure drops to 17% in the remaining areas. This last figure, however, is characteristic of the overall brick pattern, while the greater resorting to laying the bricks side by side in the area between the chains appears to be explained by the greater ease of laying them this way and by the necessity of covering the chains of the extrados that intersect the intrados at the centre of the vault. The brick pattern is very regular and, in general, the principle of alternating the joints is respected. Only in some places is there a greater concentration of alignments that contrasts with the general arrangement of the other areas. The particular position in which this has been found, that is, about 30 cm from the chain, leads to the hypothesis that this could indicate the joint between one portion of the vault and another. In the area of the centre of the vault, contrary to what has been noted in coeval vaults, there is no doubling of the courses or other irregularities in the brick patterns. There is only a greater joint thickness and the placement of a thin slab of slate.

In the transversal arch the brick are arranged alternately side by side and head to head. The arches present a coherent siding for about a metre; in the part closest to the vault this is made up of fragments of bricks and stone held together by abundant mortar. In the upper part the bricks are prevalently arranged in an orderly fashion: «di piatto» (horizontal alignment) in the parts near the perimeter wall; «di coltello» (vertical alignment) in the remaining part, Figure 7.

The shallow longitudinal arches are entirely of brick, with no insertion of stone, an expedient that is usually necessary in case of filling and adherent construction. There are some slight variations in the joint thicknesses. This too could be an indication of the care with which this structure was built.

Figure 7
Support of the transverse arch
The stone

There are few stone elements inserted into the vault. They are essentially constituted of slabs of slate of the best quality, with a thickness of between 5 and 12 centimetres, and of coarse workmanship about their edges. Probably only partly dressed, they were used here in the same form in which they arrived on the construction site. On the other hand, their characteristics turn out to be optimum for creating a valid key («tie») between the vault and the large arches above. In the case of the smaller slabs, rather than having a single element in the arch and in the vault, there are two elements one above the other, one in the arch and an analogous one in the vault. These ties are rather frequent: on the average every 25 brick courses. These elements are placed in any case at the points of the greatest force (for example, in the centre in correspondence with the wall, between the first transversal arch and the reinforcing arch, etc.). The large slabs are always, in the sample area, arranged obliquely.

A RECONSTRUCTION OF THE SYSTEM OF UNDERPINNINGS USED

An archaeological analysis of the elevation was fundamental to understanding the sequence with which the complex operation of underpinnings was undertaken in order to allow the realisation of the vault beneath a pre-existing wall. In particular, the stratigraphic analysis based on the observation of the interface between the various elements (vault, transversal arch, longitudinal arches), of the mortar joints, of the presence of chips or scales permitted a reliable determination of the successive operations undertaken. For example, in order to determine the sequence between the transversal arch and the vault an examination of the mortar turned out to be most useful. The mortar bed of the vault, spread on its extrados, contains the imprint of the bricks of the arch above. On the other hand, the mortar of the arch presents a clean continuity with respect to that of the vault on which it rests. The arch is therefore stratigraphically posterior.

In the longitudinal wall and transversal wall 2 can still be seen some elements that, in all probability, must have been employed in the underpinning operation. Wall 2, precisely in relation to that operation, was emptied with a large opening in the form of an arch. In correspondence with the left side of the opening, at approximately 1.2 meters from the apex of the arch of the extrados, there are still visible some wooden wedges and a piece of iron. The wedges have a reduced thickness (a maximum of 2 cm), and are approximately 10 cm wide and 20 cm long. They are arranged in three series: two next to each other, with five elements one on top of the other; one, with only two elements, that abuts the opening. Figure 8. The iron bar, inserted in this last portion of the wall as well, is some 2 cm thick and 7 cm wide. At the moment its length cannot be defined, but it is surely of notable dimension. The iron bar and the series of two wooden wedges are placed between two blocks of limestone; in correspondence with the two series of five wooden wedges, one above and one below, there is instead a layer of mortar about 2 cm in thickness. Between the two series of five wedges and the ribbing of the vault is placed a wooden mounting with a circular section of about 20 cm in diameter, inserted within the masonry. The mounting and the wedges are of different kinds of wood.

Wooden elements (wedges?) and some small iron bars are also inserted perpendicularly in the longitudinal wall. They are placed at different heights with respect to each other, varying from 70 cm to 123 cm with respect to the extrados of the transversal arches. The different levels of these

![Figure 8](image-url)

Transversal wall 2. The wedges used for the underpinning are shown
elements should perhaps be seen in relation to the portions of the wall to be demolished, which turn out to be different depending on whether there is a correspondence to the area in which the arch that was above the vault was to have been constructed, or of the area in which only the vault was to have constructed. It is possible that an accurate study of this could furnish interesting information regarding the dynamics of the underpinning operation. Currently being studied is the role played by the small wooden beams, the heads of which can be seen projecting along the wall at a level of approximately 50 cm from the extrados of the arches, Figure 9. These also seem to be connected to the underpinning operation.29

The underpinning operation was then undertaken thus:

1. the partial demolition of the wall (of a dimension necessary to permit the insertion of a single arch of 1.0 to 1.5 m);30
2. the realisation of a portion of the vault (leaving the ties as required);
3. the realisation of the first transversal arch;
4. the resting of the wall on the first transversal arch by means of the filling of the residual opening;
5. the partial demolition of another part of the wall;
6. the realisation of a second portion of the vault (with the necessary ties);
7. the realisation of the second transversal arch;
8. the resting of the wall on the second transversal arch;
9. . . . a repetition of this same sequence for each of the transversal arches;
10. the demolition of the portions of wall between arch and arch;
11. the realisation of the shallow arches that connect the various transversal arches;
12. the resting of the wall on the shallow arches.

The most delicate aspect of this type of operation is due to the settling that can eventually occur at the end of the operation. At this time, given the results of the archaeological analysis, there does not appear to have been any particular problems at the time of the construction campaign.

DELIMITING THE CONSTRUCTION CAMPAIGN

The operation at the beginning of the seventeenth century described above is in all probability tied to the construction, or reconstruction, of the adjacent chapel, where, in 1631 the ashes of the Venerable Battista Vernazza, abbess of the convent who died in 1587, were transferred.31 The longitudinal wall weighs on this space (measuring 5.25 by 5.75 metres) as well. The archaeological survey of the façade, executed before the actual plaster was set, indicates a series of small wooden keys that correspond to the height at which the longitudinal wall intersects, on the interior, the vault below. On the façade the keys turn out to be positioned at the lower limit of a tract of wall comprising square stone ashlar, a masonry device that is typical of the medieval. In the portion of the wall below, in any case, is found a mixed kind of modern masonry, that is, of a later epoch. The mensiochronological and mortar analyses conducted on several points on the interior confirm the hypothesis, placing the construction campaign
securely within a period contemporaneous with that of the vault that was the subject of the present study.

The fact that the two campaigns, the one regarding the space covered by the pavilion with lunettes and the other relative to the chapel, were contemporaneous partly explains the double concatenation of the wall on which the vaults of both weight. This wall contains a relieving arch that is analogous to the transversal arches of the vault, which can also be connected to the method of underpinning. A first pair of chains is situated at the impost of the arch, its anchor element is visible. A second pair of chains, buried in the thickness of the wall at approximately 2.0 metres above the ground level, cross the entire length of the wall and insure the integrity of the longitudinal walls. These are similar in their fabrication and dimensions to those characterizing the whole of the campaign. This concatenation of the surrounding walls can be found only on this side and does not appear to be present on the opposite wall. It is possible that this difference is not coincidental but is rather tied to (empiric) considerations made at the time on the different structural roles played by the two walls. Even if the insertion of the chains in the surrounding walls of the vaulted spaces is provided for in the documents, in reality it turns out to be of scant practicality. Its use in this construction campaign could therefore be consistent with the desire for security that is evident in the project as a whole.

THE STRUCTURAL ANALYSIS OF THE INTERVENTION

The construction of the vault, built under the pre-existing medieval wall, is an example of great interest both from the historical and technological point of view as well as from the structural one. This architectonical element allows us to understand the true capacities of the arch structure. It is obvious, in fact, that the rule-of-thumb methods and the criteria of geometrical proportion could not be directly applied to such a particular problem, without a knowledge of the structural behaviour.

The builder’s worries for such a delicate and unusual intervention led him to adopt a hybrid structural solution for the chain system. Besides the traditional “slinging chain”, made of an extradossal chain with two additional inclined elements that connect it to the springers of the arch, an intradossal chain was added, an unused solution at that time because of its visual impact, but considered unavoidable in this case.

To evaluate, today, the structural behaviour of a vault we can, usually, refer only to the static equilibrium conditions. Assuming the deformability of the arch to be negligible and not resistant to tensile stress, a balanced solution may be found through the well-known graphic constructions. Using this approach, it is also possible to analyse complex vaults, reducing them as a composition of arches; the safe theorem assures us of the equilibrium of the actual structure. After checking the arch (or the vault), it is necessary to evaluate the support structures, in order to see if they are able to support the horizontal forces.

In the present case this approach is not sufficient, because the redundancy of the system imposes an analysis of the complete structure. It is not, in fact, possible to estimate, a-priori, the distribution of the horizontal force in the two chains, nor the contribution of the «sling chain», nor the deformation of the lateral walls.

We have, therefore, used a numerical approach through the definition of a finite element model. This method allows us to simulate, with sufficient accuracy, the different constructive details and the behaviour of the materials. In particular, we used the Fem code ANSYS 5.5, in which the constitutive model for masonry developed by Gambardella and Lagomarsino (1997) has been implemented, which permits the simulation of the progressive degradation of the stiffness (due to the cracking), as well as the actual tensile and compressive strengths and the presence of the friction, that limits the sliding in the mortar joints.

To study the system we have decided not to consider the 3D of the structure, both in relation to the constructive phases and to the shape of the structure, constituted by a number of parallel arches. From the building we have extracted a plane structural macro-system, made of the masonry arch, part of the vault, the chains and the lateral walls (modelled in the portion between two successive floors). The mediaeval wall, built on the keystone of the arch, is considered as a load, avoiding any eventual structural effect in the transversal direction.

The arch and the lateral walls have been modelled through a four-node element, in plane stress. The
chain system has been simulated through link elements, while a beam, which is linked to the masonry by gap elements, models the anchor. These guarantee a contact only in the case of compressive stress. The model is shown in figure 10, seen as solid by the attribution of different thicknesses to the different elements.

The material parameters are the following:

- **masonry:** $E = 2500$ MPa (elastic modulus); $\nu = 0.2$ (Poisson coefficient); $\rho = 2000$ Kg/m$^3$ (density); $\sigma_c = 4$ MPa (compressive strength); $\sigma_t = 0.15$ MPa (tensile strength);
- **iron:** $E = 210000$ MPa (elastic modulus); $\rho = 7850$ Kg/m$^3$ (density).

The fem model has been constrained at the ends of the wall, in correspondence with the other floors.

The individuation of the executive phases of the intervention, deduced by the stratigraphical analysis, suggests us to consider as load-bearing only the arch and the corresponding portion of the underlying vault, as we assume that the remaining part of the vault was built up after the removal of the propping structure. However, the notable thickness of the vault (25 cm) should indicate that in the design of the builder the entire vault works together with the arch, thanks to some trick in the propping sequence. Thus, two different models have been considered: A) the arch and the underlying portion of the vault; B) both the arch and the entire vault.

The first step of a finite element analysis of a complex structure is the evaluation of the elastic response, which doesn’t consider the failure of the materials; this analysis gives a clear understanding of the behaviour for low actions and, usually, is enough for the operational conditions. In the presence of cracks, the linear analysis helps, anyhow, the interpretation of the instability, as it describes the situation just before the failure. The non linear analysis is, on the other hand, necessary to evaluate the safety of the structure with respect to the collapse, that is to know how much a given load may be increased before the total failure of the building and not only by considering local cracks. In this case both the analysis have been performed, as the load induced on the vault by the mediaeval wall is relevant.

In Table 1 the main results of the two models (A and B), by considering the linearity of the materials or the above mentioned non linear constitutive law, are showed; in particular they are: the largest values of the stresses in the crown of the arch, tensile stress at the intrados ($\sigma_t$) and compressive stress at the extrados ($\sigma_c$); the vertical displacement in the crown ($u$); the tensile stress in the two iron chains, the upper ($\sigma_{\text{upper}}$) and the lower one ($\sigma_{\text{lower}}$).

The results clearly show the relevance of the non linear analysis, for a correct interpretation of the structural behaviour. Indeed, in the linear analysis the tensile stress in the crown of the arch results
Table 1. Results of the finite element analyses

<table>
<thead>
<tr>
<th>Model</th>
<th>$\sigma_t$ [MPa]</th>
<th>$\sigma_m$ [MPa]</th>
<th>$u_l$ [mm]</th>
<th>$\sigma_{extrados}$ [MPa]</th>
<th>$\sigma_{envelope}$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model A - (linear analysis)</td>
<td>0.41</td>
<td>-0.95</td>
<td>2.4</td>
<td>19.3</td>
<td>15.9</td>
</tr>
<tr>
<td>Model B - (linear analysis)</td>
<td>0.25</td>
<td>-0.85</td>
<td>2.2</td>
<td>23.9</td>
<td>18.4</td>
</tr>
<tr>
<td>Model A - (non-linear)</td>
<td>0.12</td>
<td>-1.02</td>
<td>2.7</td>
<td>19.7</td>
<td>17.4</td>
</tr>
<tr>
<td>Model B - (non-linear)</td>
<td>0.14</td>
<td>-0.92</td>
<td>2.3</td>
<td>24.0</td>
<td>18.5</td>
</tr>
</tbody>
</table>

inadmissible with the masonry strength; on the contrary, the non-linear analysis considers a cracked zone, in which tensile stresses are significantly reduced, with a consequent increasing of the compressive stresses in the extrados; moreover, also the vertical displacement and the pull in the chains increase. Moreover, the analysis of the results shows the important role of the vault; indeed, if all the mediaeval wall weighs only on the arch, the tensile stresses would be too high to be sustained without wide cracks. Instead, if the constructive phases were such as to weigh also the entire vault, the structural system would result appropriate, as proved by the fact.

Finally, some considerations are addressed to the system of chains. The finite element analysis shows that both the intradosal and the extradosal chains work significantly, while the inclined chain are completely unloaded. It is worth noting that the slinging system (extradosal chain plus two inclined ones), used in order to hide the chains, has a doubtful effectiveness; this fact may be deduced both from structural analyses and by direct observations (in many cases the inclined chain appears to be inarticulate with the extradosal one, in correspondence of the connection). In this particular case, due to the difficulty of the intervention, the builder adopted a double security, by adding to the system also the intradosal chain; this fact made the inclined chains almost useless.

NOTES

In this paper, the structural analysis was written by Sergio Lagomarsino (DlSEG, Università di Genova), the first four paragraphs were made by Anna Boato (DSA, Università di Genova), the remaining part was made by Daniela Pittaluga (DSA, Università di Genova). Drawings by A.Boato and M.Sarcina.

1. With reference in particular to an inter-university research project entitled «Costruzione voltate in muratura» («Masonry vault construction») undertaken in the years 1998–2000 in which Anna Boato and Daniela Pittaluga participated, in the context of the Genoa operative unit coordinated by Prof. Paolo B. Torsello (see Boato 2001; Pittaluga 2001).

2. The pavers were a little smaller and thinner than bricks of the same age.

3. Corresponding to standards of deviation that were relatively low.

4. A palm is equal to 24.776 cm (Rocca 1871).

5. For example, this can be seen in the following document, in which the choice whether or not to use a chain is dictated by the builder: «tutte queste stanze vanno in volta [di] mezza botte o a crocera senza ferri o con ferri bisognano ma ben secure et ben fatte, «all these rooms are to be vaulted with barrel vaults or cross vaults without irons or with irons as need be but well secured and well made» (Archivio di Stato di Genova, Notai Antichi, 1840, 22 February 1549).

6. «... mettere ad ognuna di dette volte i telari de chiavi con suoi bracci di ferro da quattro a fascio con stanghette per lungo e per traverso de manera che sijno molto forti e secure. «... put on each vault the key frames with its iron branches four to a strip with small bars longwise and crosswise in such a way that they are strong and secure» (Archivio di Stato di Genova, Notai Antichi, 5137, 8 August 1629).

7. The church and its annexes, among which are the object of this study, correspond to number 34 in Piazza Santa Maria in Passione, which today is the property of the Università degli Studi di Genova.

8. The width of the space above various from approximately 3.15 to 4.0 meters; its total length is equal to 16.4 meters. The difference in length could be due to the fact that only the area that could be effectively used by the nuns was taken into consideration, to the exclusion therefore of the part that is the presbytery.
9. It has not been possible to verify the physical continuity of the anchor elements. However, in the only situation where there is almost complete visibility there has been several proofs of this. It can be seen above all in the two lengths of anchor element that are visible thanks to studies undertaken on the plaster that covers it. The section of this is equal (about 5 cm by 5 cm, and it remains constant for the whole part that is visible. This indicates naturally that it could be a single element, but it also constitutes an anomaly with respect to the wedge form that usually characterizes the Genoa anchor elements. Such an anomaly could however be explained precisely because the anchor element is a single element: its setting in place through several eyes, placed each a certain distance from the others, and its being placed under uniform stress are in fact rendered easier by a anchor element of a uniform section, aided by metal wedges placed separately in the several eyes (in fact, such wedges are indeed present).

10. The various pavements and rafters sat on the rubble; these were removed during the course of the restoration work.

11. The selection process could have been executed on the work site or could have been due to the acquisition of materials of a different quality.

12. The presence of lime gravel (or crudi) can be noted in many structures.

13. A correct interpretation of the data relative to the mortar must take into account the possible degradation that could have had a considerable influence on these characteristics.

14. These considerations are possible only if a large number of coeval structures are available for study.

15. For example, the analysis undertaken on 139 bricks related to the structure in question indicate a standard deviation of 0.27, a value that is relatively low for the seventeenth century. This could be related either to the extremely good quality of this lot of bricks or to a careful selection of the elements to be employed.

16. Medieval bricks, probably obtained from the partial demolition of the wall underneath which the vault was constructed, were found in the supports of the transversal arch and in the structure above the climbing arch that terminates the vault.

17. The observations were made in the visible areas: at the extrados near the center of the vault and at the intrados in correspondence to the last two transversal arches, which are also in the area at the center of the vault.

18. This data is also contrary to what is usually to be found in other structures of the same period. In fact, there is often an alignment of the joints in two (and, more rarely, or three or more) courses.

19. The vaults taken into consideration where those destined to be covered in plaster, as was the seventeenth century vault of Santa Maria delle Grazie.

20. The observations regard a portion of the vault examined at the intrados. Even though it was a small portion, it is fairly significant because, since it regards the area in the center of the vault, it allows the observations of one of a zone that is most characteristic and sometimes contains the greatest number of anomalies in the pattern.

21. One course is constituted entirely of brick headers (which means that on the side of the arch only a single brick can be seen); the next course is constituted of brick lengths (on the side of the arch there are two bricks that are visible). In the thickness of the arch there is the hook of the chain of the extrados with its bracci or arms: in correspondence to this several small anomalies are found in the brick pattern of the arches.

22. On the whole, the solid supports at the two extremes of the arch concern 2/5 of the width of the arch itself.

23. The elements of lesser thickness usually present a simple bevel at their edges, while those of a greater thickness generally have a «prismatic» profile.

24. At the intrados the large slabs of slate are not visible; the visibility is limited to only a few zones. It is, however, possible that the slabs, even if they do not concern the entire thickness of the vault, and in some case of the vault and the large arch above, are in any case such that they create a ring of at least 2/3 of the entire thickness.

25. The additional observation of the relationship between transversal arch and shallow connecting arch and, in the case of the end portion of the vault, of a tie of the longitudinal climbing arch to the transversal one, has permitted the reliable determination of the chronology of the construction campaigns.

26. These are two blocks of lime marly limestone of some 15 cm by 20 cm placed immediately above and below the wooden wedges and the small iron bars. The upper block presents noticeable signs of degradation; this should be related to the way they were handled when they were «pushed» into place.

27. Unfortunately it was not possible to observe how this element was placed with respect to the transversal arch. In the lower part, in fact, where it touches the arch, the wood is extremely decayed. Further, work recently performed block the visibility of the extrados of the arch precisely in correspondence to the hypothetical point of contact between the wood and the arch. The wooden mounting may be in relationship to a hidden chain that passes diagonally in front of it and dies within the arch. The role of such a chain has not yet been clarified.

28. The heads of these iron elements have average dimensions of 2 cm by 8 cm.

29. The wooden rafters have a circular section with an average diameter of 8 cm; they are placed approximately 70 cm from axis to axis. Wood chips are
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...to be found all around the rafters. Elements that are similar in shape, position and direction are found in the walls opposite them. The stratigraphic analysis of the portion of the adjacent masonry the rafters will be fundamental in the clarification their role in the underpinning operation, so that their context and later insertion can be determined. Other tests that could be performed are the dendrochronological examination of the rafters to determine their dating and an analysis of the mortar in contact with the wood.

30. To determine the limits of the construction campaign it would be necessary to perform a stratigraphic analysis on the lower portion of the longitudinal wall, which is, however, plastered and ornamented. A doubt remains about the dimensions of the cases of the largest arches: were they made at one time or at different times? A detailed analysis of one of these arches, and in particular on the mortar joints, could provide good results.

31. This date is provided by the memorial stone that is still in place in the end wall. The eighteenth-century style stucco decorations are therefore to be attributed to a later redecoration.

32. The dimensions of the brick can in fact be dated back to the first decades of the seventeenth century and the mortar turns out to be constituted of the sand of Sampierdarena.

33. This is understandable precisely when seen in relation to the daring of the campaign.

34. These chains turn out to be at the same height at which, in the space, are found the chains of the intrados.

35. The chains utilized are generally of a square section of approximately 5 cm per side. They present signs of hammering with a rounding of the corners. On the chains of the intrados it is possible to see the points where the single pieces used were welded. On average, the length of the bars is approximately 2.0 m.

36. This wall is plastered and covered with stucco decoration, so consequently it is unthinkable to perform any investigations. It has been inspected in correspondence to the right side, and on the portion that is visible there appears no sign of any anchor element, though the presence of chains cannot be excluded in the part that is not visible. It has not been possible at present to verify this with a Geiger counter.

37. This much has emerged from the analysis of what exists. The databank contains more than 300 structures and was realised by D.Pittaluga (with the collaboration of E. Calza, L. Chiappe, M.S arcina, P. Pittaluga, A. Canziani, L. Comino) with the assistance of G. Beltrame and F. Ciribi (curator of a databank at the Faculty of Architecture at the University of Genoa regarding research on vaulted structures that has been undertaken in the last ten years).

**Reference List**


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