RETROFIT OF A COLLAPSED MASONRY GALLEY WITH HISTORICAL VALUE: PRELIMINARY STUDY OF ALTERNATIVE SOLUTIONS AND RETROFITTING STRATEGIES

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ABSTRACT

This work presents a preliminary study aiming at singling out the most suitable design solution for the retrofitting of a collapsed masonry barrel vault placed in the central archaeological area of Rome, in Italy. Main objectives to be pursued with the restoration are: 1) re-opening the monument to the public, and 2) endowing it with a walkway on the extrados of the vault in order to allow visitors enjoy the sight of Circus Maximus. The paper is divided into four parts, as follows: 1) firstly, a description of the current status of the monument is provided, then 2) based on the results obtained by simple mechanical models, the possible causes of the collapse are discussed, 3) some reconstruction strategies are presented and compared to each other, also in economic terms, and eventually 4) the motivated selection of the final solution to be implemented is presented.

Keywords: Architectural heritage, barrel vault, monument, preliminary design, retrofitting.

INTRODUCTION

The conservation and restoration of an archaeological monument are a challenge for engineers and architects.

Most often, these artefacts are the result of a long process of transformations and stratifications that have occurred over the centuries, and that have ended up modifying the monument in terms of a) original structural behaviour, b) form and c) function, so that the result with which technicians have to deal with is a very complex and unique structure.

Uniqueness and complexity require special attention and care both in the evaluation of techniques and technologies to be used in the restoration (either consolidation or seismic amelioration design), and in the choice of materials. In fact, when working on an important monument of historical-architectural value, the design solution to be searched is always the one that guarantees the best compromise between need to intervene and necessity to bring the minimum disturbance to both the structure and its surroundings.

Moreover, it is essential to understand which materials to use in order to build any missing and/or additional parts, without altering the “image” of the artefact. For this reason, it is necessary a multidisciplinary approach that integrates all different expertise, hopefully involving architects, archaeologists, historians, and engineers (e.g. Roca et al. 2010).

Stability and durability are also necessary conditions, but not sufficient to define the criteria and to choose the intervention techniques, having to prefer the preservation of the monument.
in its environmental context and in accordance with its forms and structural design (DPCM 2011).

The restauration works to be carried on archaeological artefacts must be guided by the criteria of both “integration” and “integrality” (e.g. Elia 2010).

The present work deals with the study of alternative restoration and seismic amelioration solutions of a vaulted gallery, in the Central Archaeological Area of Rome. This latter includes important archaeological monuments and offers a vast range of typologies and typical (own) Roman architecture construction techniques (e.g. Lugli 1957).

In particular, these monuments are characterized by the presence of arches and vaults, that the Romans built in various forms and in various ways. Initially, the arches were made of stone blocks or bricks while later, with the introduction of the pozzolanic mortar, particularly resistant, and mixed with stones of various sizes, vaults were built by the technique of the concretion, also called *opus caementicium*. These vaults were designed as a monolith that is as a single block of stone that would not have to exert horizontal load on retaining walls.

![Bricks and vault](image)

**Fig. 1** - Bricks and vault: a) size of the bricks used in roman constructions; b) three-dimensional view of an *opus caementicium* vault with the semilatere ribbing (image from Tomasoni 2015).

In fact, the *opus caementicium* could not ensure such a monolithical structural behavior since it does not have a reliable tensile strength and for this reason, the occurrence of cracks turned the vaults into pushing systems. From a construction point of view, the *opus caementicium* was poured on a temporary structure made of wooden ribs that was subsequently removed.
after its hardening; for this reason, in structures built by this technique, traces of such wooden ribs remain impressed in the intrados surface.

Later, Romans began to select the materials constituting the various layers of the vaults and to sort such materials according to their specific weight, and implementing them according to the static needs. For instance, in the dome of the Pantheon, light volcanic stones, that are pumice stones, can be found in the top layers (e.g. Croci 2005). From the 1 century a. D., the opus caementicium vaults were built with the so called semilateres that are brick ribbings positioned along the directrix of the barrel vault and connected to each other with bipedales bricks (Fig. 1a, b). These ribbings had the function to stiffen the structure, and to confine the fresh concrete mass.

Any design proposal that involves the statics of a historic building should be based on: 1) an accurate geometric and material survey, and 2) the interpretation of the static behaviour, so as to highlight the critical points of the building (yielded from either original conditions, intentional transformations, degradation or accident).

For this purpose, a part of this work has been dedicated to understanding the causes that may have led to the collapse of the gallery, by means of simple mechanical models, to verify both its static and seismic safety. This study is being essential to direct the development phases of the design strategies and to define what might be considered the best solution in terms of "advantages and disadvantages", i.e. in terms of a) total or partial achievement of all the goals, b) respect of the restrictions, and c) the level of operational and economic feasibility.

Since the XV century studies about the static vaults were developed, but the first static theories about the arches, vaults and domes, date back to the XVII century. Important is, for example, the de La Hire’s contribution (e.g. de La Hire 1730,1731) who first used the funicular polygon construction in the static analysis of the arches. Couplet (e.g. Couplet 1731,1732) introduced the concept of rotational hinge as a condition for the fracture. Coulomb (e.g. Coulomb 1776) based his studies on finding the collapse safety factor and introduced the friction and cohesion conditions between the blocks. During the XIX century, starting from Navier, attention was also paid to the strength of materials to determine the application points of resultant forces in the keystone and in the fractures joints. An early study about the pressure curves was conducted by Mery (e.g. Mery 1840) who proposed a graphical verification method of the arches that is still used nowadays.
Currently the analysis and verification methods about the safety of arches and vaults are numerous. The most significant studies developed over the past years encompass: 1) the theory of plasticity and limit analysis applied to masonry structures (e.g. Heyman 1996, 1982; Monti et al. 2013; Tomasoni 2015); 2) the membrane theory, which takes into account the three-dimensional effects (e.g. Flugge 1973); 3) the analysis of the vaults through the finite element modeling according to a "continuous" or a "discrete" approach (e.g. Lourenço 2002; Roca et al. 2010). In particular, the limit analysis method has been proven to be one of the most powerful techniques for engineering practice, due to the suitable compromise between relative simplicity and prediction accuracy. In a preliminary phase, this method appears the most appropriate and effective tool to verify the structures.

CURRENT STATUS OF THE MONUMENT

The so-called Galleria delle Volte Crollate (The Collapsed Vault’s Gallery), object of this work, is part of an important archaeological site – the Augusto’s House on the Palatine hill – which has not been completely explored yet. This site is therefore the subject of preliminary assessments, both historical and archaeological, which are being studied by experts in this field.

The Gallery is located in the central archaeological area of Rome, precisely in the south-west area of the Augusto’s House (Fig. 2) and it was originally roofed by a depressed barrel vault made by a conglomerate composed of irregularly shaped tuff stones and pozzolanic mortar, according to a technique called opus caementicum. At a certain point of the history, and for unknown reasons, the vault must have collapsed disintegrating in large conglomerate blocks.
These resulting blocks, probably remained buried under soil and rubble for a long time, were rearranged, according to a restoration design of the second half of the twentieth century (between 1960 and 1980), by a complex and heterogeneous system comprising 1) steel beams, 2) squat brick masonry walls, and 3) wood struts (Fig. 3). That design was meant to restore the vaulted passage in order to make it usable by visitors. Only some portions of the vault are still standing in their original place. The structures beneath the quota in question, including the foundations, have not been excavated yet.

Anyway, the gallery is currently closed to the public. The status of the gallery, at a first sight, does not appear to be safe enough to allow access to the visitors. Among the aspects that give rise to some concern, are: 1) some of the wood struts are cracked, slightly damaged at their extremities and probably not safe with respect to the buckling phenomenon, 2) some of the steel beams are oxidized and with a flexural curvature that can be appreciated by naked eye (Fig. 3), 3) static safety in some points relies on mutual contrast and interlock between adjacent blocks that, in correspondence of the contact point, due to the high concentration of stresses, are visibly cracked with resulting dusty rubble and likely loss of stability. Moreover, in correspondence of the north-western entrance to the gallery, the downhill wall is undergoing an outward rotation.

An accurate survey of the monument was carried out in order to determine 1) the geometrical dimensions and relationships among the different parts it is composed of, 2) the constitutive materials, their state of conservation, and relevant physical and mechanical properties (qualitatively, by comparison with literature data), 3) the original structural conception and possible successive modifications. As to the geometrical features, the vault is a barrel depressed arch and its spring line \((L)\) is 4.45m and its rise \((f)\) is 0.59 m (Fig. 7). For what concerns the materials: 1) the “structural part” of the vault is made of tuff conglomerate and pozzolanic mortar; 2) the filling layer is constituted by two layers: the former in mortar and flint aggregates and the latter, a thinner layer, in “cocciopesto” aggregates (Fig. 4). The extrados shows traces of the so-called “suspensurae” (brick walls spaced apart that created a ventilated interspace) and a pavement in bessali (Figs. 1a, 4) that leaves guess that the gallery was also accessible at the extrados (Fig. 4).
The gallery walls are characterized by different construction techniques. On one side, the vault lied on a brickwork masonry (*opus testaceum*) and on the other, on a mighty wall of tuff and travertine blocks that today stands at a height much lower than the original one.

A detailed survey of all the steel beams was carried out (type, span, degradation), by numbering 41 beams in total (39 double T steel beams and two wooden ones). The safety verification about the steel structures (Di Miceli 2016) has highlighted a situation of possible risk: a) 29 beams are not verified for flexural static loads, and b) 4 are not verified for both flexure and shear (Table 1). These first results, therefore, suggest to reconsider the twentieth-century intervention, eliminating the steel and wood supporting structures and proposing possible alternative solutions for the vaulted roof of the gallery, according to a more correct interpretation of the monument structures.

### Table 1 - Excerpt of the results of the steel beams safety analysis (Di Miceli 2016).

<table>
<thead>
<tr>
<th>Beam</th>
<th>Rise</th>
<th>Type</th>
<th>FLEXURE</th>
<th>SHEAR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[m]</td>
<td></td>
<td>cap/dem</td>
<td>cap/dem</td>
</tr>
<tr>
<td>1</td>
<td>4,36</td>
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<td>0,92</td>
</tr>
<tr>
<td>2</td>
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</tr>
<tr>
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<tr>
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</tr>
<tr>
<td>6</td>
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<td>not verified</td>
<td>0,72</td>
</tr>
<tr>
<td>7</td>
<td>3,7</td>
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<td>not verified</td>
<td>0,34</td>
</tr>
<tr>
<td>8</td>
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<td>not verified</td>
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</tr>
<tr>
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<td>11</td>
<td>3</td>
<td>INP 120</td>
<td>not verified</td>
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### POSSIBLE EVOLUTION OF THE MONUMENT

Starting from the study of the bibliographic sources (e.g. Iacopi *et al.* 2006; Pensabene *et al.* 2011, 2013; Carandini *et al.* 2010), two different hypotheses about the architectural genesis of the so-called *Galleria delle volte crollate* were taken into account:

1) the Gallery may be considered a vaulted substructure lying on the soil, and directly cast on it, as a support of the bases in front of the *Apollo’s Temple*, which was part of the *Augustus’ House* (Fig. 5). From a structural point of view, therefore, its stability would be related to the bearing capacity of the underlying soil;

2) the Gallery is a self-supporting vaulted structure, with depressed cross-section, and its stability is related to the mechanical properties of materials and its geometric shape.

The first hypothesis would be supported by the fact that, when Augustus decided not to further expand his house in favor of the construction of the *Apollo’s Temple*, he also decided to bury all the previous structures and to raise the walking level. The construction of the vaulted
gallery would be, therefore, contemporary with the construction of all the substructures in front of the Apollo’s Temple. Another element in favor of the first thesis is that the barrel vault would result supported, along its longitudinal development, on vertical structures made in different ages and by different techniques, that are: 1) on the southern side, on the remains of a brickwork masonry and, 2) on the northern side, on a wall with tuff and travertine blocks (Fig. 5).

In support of the second hypothesis, however, some literature sources claim that the Gallery would have been built as a vaulted walkway that connected the rooms of the western peristyle of Augustus’ House with the structures of the eastern peristyle (Fig. 5). These latter have a vault that is very similar, in terms of both materials and geometry, to that of the Gallery in question and therefore it was very probably built in the same timeframe (Fig. 6a). Another element, which would suggest that the gallery was built as a self-supporting structure, is represented by the traces of the wooden planks still recognizable at its intrados (Fig. 6b).

In the next section, all these assumptions have been reevaluated also on the basis of the results obtained by means of simple, yet efficient computing models, trying to identify the causes that may have led to the collapse of the vault, thus trying to answer the following questions:

1) Did the vault collapse due to the fact that it actually was a depressed vault?
2) Did the weight of the fill above, not foreseen by the original design, cause the collapse either in static or seismic conditions?
3) Was the collapse of the vault caused by the illegal removal, according to an unfortunate and widespread practice of the time, of some tuff and travertine blocks of the perimeter walls thus weakening the supports of the vault itself? Note that similar episodes have been unfortunately occurring in other monuments of the Palatine.
PROBABLE CAUSES OF THE COLLAPSE

The safety of the arch, in its original features before collapse, was verified by means of simple mechanical models in order to have an expeditious and preliminary estimate. The arch safety was analysed against both static and seismic loads. Such a study can also be useful 1) to avoid to reconstruct a structure that was affected by design mistakes and 2) to better address the decisions to be taken in order to retrofit the gallery and make it usable by the visitors of the Palatinum Area.
Static Loads

The verification under static loads was carried out by means of Mery’s Method (Mery 1840), verifying if, for a uniformly distributed load (self-weigh plus fill), the thrust line is contained within the core of the arch. In that case, the arch would result safe, according to Mery.

A one-meter deep portion of the barrel vault was analysed. The Mery’s method was translated into analytical formulations and implemented in a simple computer program. The arch was discretized into a large number of blocks in order to calculate the various involved parameters, that are, for instance: the weight of the vault and its overlying fill (Fig. 7).

The verification shows that the thrust line is entirely contained within the core (Fig. 8a). But this result is not reliable enough to draw positive conclusions about the safety of the arch since the model is affected by a drawback. In fact, since it imposes the passage of the force resultant through both 1) the uppermost extremity of the core, in correspondence of the keystone, and 2) the lowermost extremity of the core, in correspondence of the imposts, it ends up providing, for static distributed loads, and whatever geometrical contour conditions, a thrust line that is always contained in the arch core. Thus, that result could be misleading.

So a normal stress verification was carried out in correspondence of the arch sections in which the vertical weights, due to both the filling and the blocks’ self-weight, are combined with the horizontal force applied to the keystone (Figs. 8b and 9).

For the mechanical properties of the constitutive material, rubble tuff block masonry, (Circolare Esplicative n°617) the unit compressive strength was assumed equal to $\sigma_R = 140.0 \, \text{N/cm}^2 \). The trend of the ratio between the masonry strength and demand, along the arch length, in terms of compression $\sigma_R/\sigma_S$, is plotted in Fig. 8b. As can be gathered from this trend, which is plotted for different values of the structural masonry unit weight ( $15.0 \leq \gamma_m \leq 25.0 \, \text{kN/m}^3 \)$, the ratio $\sigma_R/\sigma_S$ ranges from a minimum value of 2.50 and a maximum value of 7.20. Note that the trend of the ratio $\sigma_R/\sigma_S$ along the arch shows a singular point with a change of curvature approaching the imposts that is due to the change of the sign of the thrust line eccentricity with respect to the arch mid line. It emerges that the arch was properly designed to support the gravity loads to which it was subject.
Seismic Loads

The verification under seismic loads was carried out by means of the Limit Equilibrium Analysis Method, assuming for the arch a collapse mechanism according to which four hinges divide it into three rigid blocks (I, II and III in Fig. 10). Such labile mechanism has one degree of freedom that is the downwards rotation $\theta_1$ of the block $C_1C_2$, while the rotations of the remaining two blocks, $\theta_2$ and $\theta_3$ around their relevant instantaneous rotation center are kinematically dependent on $\theta_1$. The collapse mechanism, due to a seismic action directed rightwards is represented in Fig. 10. In searching for the most probable collapse configuration, coherent with the collapse mechanism above, the following assumptions were made: 1) only the case of arch portions contained in an opening angle larger or equal to $15^\circ$ were taken into consideration, 2) the first hinge $C_1$ was assumed to be located at a distance of about 5% of the arch springing line ($L$) from the left impost, and 3) the fourth hinge $C_4$ was assumed to be located at the right impost.

For the properties of masonry, the following assumptions have been taken: a) no tensile strength; b) infinite compressive strength; c) absence of any slippage, i.e. infinite friction, along the interfaces between the tuff irregular blocks and the mortar.

The horizontal seismic force that activates the overturning mechanism is defined by means of the horizontal loads multiplier $\alpha_0$, which is the mechanical ratio of the work done by the stabilizing forces with respect to the work done by the overturning forces, in accordance to the Virtual Work Principle (Circolare Esplicativa n°617):

$$\alpha_0 \cdot \left( \sum_{i=1}^{n} P_i \cdot d_{z,i} + \sum_{j=n+1}^{n+m} P_j \cdot d_{z,j} \right) - \sum_{i=1}^{n} P_i \cdot d_{y,i} = L_{fi}$$  \hspace{1cm} (1)

$$\alpha_0 \cdot L_{\text{overt}} = L_{\text{stab}}$$  \hspace{1cm} (2)

where: $P_i$ is the self-weight of the $i$-th rigid block, $P_j$ is the $j$-th carried weight, $d_{z,j}$ is the virtual horizontal displacement of the point of application of $P_i$, $d_{z,j}$ is the virtual horizontal displacement of the point of application of $P_j$, $d_{y,i}$ is the virtual vertical displacement of the
point of application of $P_i$, and $L_{fi}$ is the work of internal forces. Note that when the vertical displacements are directed downwards they positively contribute to the overturning work ($L_{overt}$), and vice-versa ($L_{stab}$).

The value $a_R$ of the spectral seismic acceleration can be evaluated as follows (Circolare Esplicativa N°617):

$$a_R = \frac{\alpha_0 \cdot \sum_{i=1}^{n+m} P_i}{M^* \cdot CF} = \frac{\alpha_0 \cdot g}{M^* \cdot CF}$$

(3)

where $CF$ is the Confidence Factor, function of the Knowledge Level $KL$; $g$ is the gravity acceleration; and $M^*$ is the participating mass, which can be evaluated by (Circolare Esplicativa N°617):

$$M^* = \frac{\left(\sum_{i=1}^{n+m} P_i \cdot d_{z,i}\right)^2}{g \cdot \sum_{i=1}^{n+m} P_i \cdot d_{z,i}^2}$$

(4)

The demand acceleration $a_D$ was assumed as the value corresponding to the constant acceleration plateau of the site spectrum (Fig. 11 and Table 2), evaluated by means of the Italian Standards for Constructions (NTC2008), and four limit states, that are: 1) Immediate Occupancy Limit State (IOLS with return period $T_{R} = 30 \text{ yrs}$), 2) Damage Limit State (DLS $T_{R} = 50 \text{ yrs}$), 3) Life Safety Limit State (LSLS $T_{R} = 475 \text{ yrs}$), and 4) Collapse Limit State (CLS $T_{R} = 975 \text{ yrs}$). The capacity/demand ratio was calculated as follows:

$$\rho = \frac{a_R}{a_D}$$

(5)

In searching for the minimum value of the collapse multiplier, all the possible collapse configurations consistent with the assumptions above, were analyzed. In doing that, the ratio
between the positive amount of the stabilizing work \( L_{\text{stab}} \), in case of vertical displacement with direction opposite to the relevant weight load \( \text{sign}(d_{iy}) \neq \text{sign}(P_i) \), and the negative amount of the stabilizing work, in case of vertical displacement with the same direction as the relevant weight load \( \text{sign}(d_{iy}) = \text{sign}(P_i) \), varies almost with continuity. In this way, the collapse multiplier can also assume either negative or very low positive values. The former ones were discarded since they do not have physical meaning while the amount of positive values were analyzed in statistical terms (Fig.12). In fact, assuming the minimum value of \( \alpha_0 \) would result excessively conservative.

\[
\text{Fig. 11 - Comparison between response spectra.}
\]

\[
\begin{array}{ccccccc}
\text{IOLS} & 0.043 & 2.539 & 0.256 & 1 & 1 & 1.4 \\
\text{DLS} & 0.055 & 2.502 & 0.269 & 1 & 1 & 1.4 \\
\text{LSLS} & 0.121 & 2.630 & 0.293 & 1 & 1 & 1.4 \\
\text{CLS} & 0.152 & 2.615 & 0.301 & 1 & 1 & 1.4 \\
\end{array}
\]

For each of the analyzed limit states, a normal distribution of the probability density was determined and the relevant value of the probability of attainment of the LS, conditioned to the given value of the peak ground acceleration, was calculated as follows:

\[
\text{Pr}\left[ \rho \leq 1.0 \mid a_g (LS) \right] = \int_0^1 D \Pr \cdot d\rho
\]

where: \( D \Pr \) is the probability density function. The results are plotted in Fig. 12. As can be gathered from that figure, the probability of failure of the several LS is: 18% for the IOLS, 25% for the DLS, 74% for the LSLS, and 86% for the CLS. This yields that the arch, in its original shape and loading condition, was not safe with respect to the seismic loads given by the Italian Regulation currently in force (NTC2008). So, it is possible to conclude that the arch might have collapsed due to an earthquake attack.
The results of the calculations would support the hypothesis that the gallery’s vault was conceived as a structural one thus disproving the hypothesis that it was obtained by simply casting the opus caementicum directly on the soil. Moreover, the traces of the wooden planks, still visible on the intrados of the vaults remaining portions, would also support the second hypothesis according to which the gallery was a structural one.

In light of the considerations above, we can conclude that the vault, even though intentionally conceived as a structural one, may have been affected by macroscopic design defects so that it was not able to withstand seismic loads and probably collapsed due to an earthquake.

**ALTERNATIVE RETROFITTING STRATEGIES**

In this section, several restoration design alternatives are evaluated in terms of both feasibility and economical expense. For each of such hypotheses, all the construction phases were first singled out and subsequently evaluated in economic terms.

Fig. 12 - Probability density of the seismic capacity/demand ratio for different limit states: Immediate Occupancy (IOSL), Damage (DSL), Life Safety (LSLS), Collapse (CSL).

Fig. 13 - Current state of the Gallery (a); integration of perimeter walls and cutting of steel beams flush against the wall so that the left portions remain incorporated in the new masonry (b).
The main objectives to be pursued are: 1) making the gallery accessible to the public, 2) recreating the original intrados surface, 3) increasing the safety of the structure for both static and seismic loads, 4) suitably organize the construction site, given the delicate surroundings, and 5) bring the minimum disturbance to both the supporting lateral walls and the underlying structures, down to the foundations. In fact, as to this latter point, the structures beneath the walls still have to be excavated and are partially unknown.

The cost analysis was carried out indicating for each constructive phase the relevant a) unit of measure (u. m.), b) unit price (u. p.), and c) quantity of each specific component, in relation to one linear meter of the Gallery’s longitudinal extension (37.27m long by 4.45m wide). Works that are common to each of the design proposals have been listed in the relevant tables but not quantified in economic terms, in order to carry out a comparative economic analysis highlighting only the works peculiar of each solution. Prices were deducted from both “Tariffa dei prezzi 2012 - Regione Lazio” (TPRL 2012) and “Listino noleggio Pernicini 2010” (LNP 2010).

Fig. 14 - Installation of possible tie rods (a), view after the demolition of the steel beams and the brick walls; similar tie roads found in another monument in the archeological area of Rome (b).
**Fig. 15 - First solution: bridge crane scheme (a); reconstruction of the vault and the floor above (b).**

### First solution

**1) Masonry reconstruction of the barrel vault with localized lifting and repositioning of the blocks with an overhead travelling bridge crane (Figs. from 13 to 15)**

<table>
<thead>
<tr>
<th>u. m.</th>
<th>u. p.</th>
<th>quantity</th>
<th>price</th>
</tr>
</thead>
<tbody>
<tr>
<td>ml</td>
<td></td>
<td>10</td>
<td>32,80</td>
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</table>

**1.1) The previous intervention in steel beams, wooden supports and brick walls is initially left in place.**

**1.2) Integration of the perimeter walls (tuff, brick and travertine) of the gallery, up to the maximum height of the vault extrados: this height is deduced from two points in which the vault is still in the original quota (Fig. 13a,b). If necessary, the perimeter walls are shaped to create the impost of the vault.**

On the north-west side (masonry blocks of tuff and travertine), where the longitudinal access openings to the adjacent Domus Augusto’s rooms can be found, the flat arches above such openings will be rebuilt, at their original impost quota.

**1.3) It will be necessary to verify that, after removal of a) wooden supports, b) squat brick walls or other blocks, the vault portion left in place is able to support both itself and the steel beams of the deck to be positioned successively; otherwise it is necessary to intervene locally with tie rods and consolidating injections (Fig. 14a, b).**

<table>
<thead>
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<th>month</th>
<th>1,470,00</th>
<th>12</th>
<th>473,30</th>
</tr>
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</table>

**1.4) The collapsed vault blocks, currently stored inside the gallery, but that are difficult to relocate properly in their original position, due to the shortage of information, are lifted by the crane and taken to the external storage area.**

**1.5) Installation of the longitudinal (assuming HEA1000 = 272kg/m) and transversals beams (HEA 500 = 155kg/m) of the steel deck (included the bracings), by means of the crane (Fig. 14b).**

<table>
<thead>
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<th>kg</th>
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<tr>
<td>kg</td>
<td>3,35</td>
<td>155</td>
<td>2,310,66</td>
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1.6) **Bridge crane** construction (installation) with two orders, where its dimensions are calibrated on the basis of both the maximum and minimum block size (Fig. 15a). Note that the cost includes the electric winch.

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</table>

1.7) The vault blocks are lifted and repositioned, with an electric winch; construction of the **wooden plank arch-centering**; these operations are done by subdividing the gallery length in successive sub-portions. After completing a sub-portion the bridge crane is moved and operations are iterated at the adjacent sub-portion.

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<td>mq</td>
<td>48,35</td>
<td>4,45</td>
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1.8) Removal of the elements composing the previous intervention (XX century). The steel beams are cut along the cross section in correspondence of the wall surface so that the left portion will remain embedded in the wall and visible to the outside, thus leaving historical memory of the previous intervention (Fig. 13b); the brick walls are demolished; transport of end products in landfill.

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<tr>
<td>mq</td>
<td>230,00</td>
<td>2,225</td>
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1.9) **Reconstruction** of the missing “structural” portion of the vault.

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<td>mq</td>
<td>49,69</td>
<td>4,45</td>
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1.10) Possible fill in lightweight material (only if it has a static function) to the extrados of the new reconstructed parts.

1.11) The **wooden plank arch-centering** is disassembled.

1.12) Construction of a floor with **corrugated steel sheet and reinforced concrete slab**: note that the beams depth is such as to leave a space that allows to preserve the **suspensurae** (Fig. 15b).

**Second solution**

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<td>2.1) Numeration and accurate survey of the current position of the collapsed vault blocks.</td>
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<tr>
<td>2.2) Consolidation of the vault blocks (for example with injections) to improve their mechanical properties and to ensure that – during the lifting stages – they will not undergo any damage.</td>
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**Fig. 16 - Second solution: masonry reconstruction of barrel vault.**
of the gallery, up to the maximum height of the vault extrados. This height is obtained by two points in which the vault is still in the origin quota (Fig. 13a,b). If necessary, the perimeter walls are shaped to create the impost of the vault. On the north-western side (masonry blocks of tuff and travertine), where the longitudinal access openings to the adjacent Domus Augusto’s rooms can be found, the flat arches above such openings will be rebuilt, at their original impost quota.

2.3) Removal of the elements composing the previous intervention (XX century). The steel beams are cut along the cross section in correspondence of the wall surface so that the left portion will remain embedded in the wall and visible to the outside, thus leaving historical memory of the previous intervention (Fig. 13b); the brick walls are demolished; transport of end products in landfill.

2.4) Construction of the arch-centering along the Gallery.

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<tr>
<th></th>
<th>mq</th>
<th>4,45</th>
<th>215,15</th>
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<tr>
<td>2.5)</td>
<td>Lifting and correct re-positioning of the vault blocks by the crane.</td>
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</table>

2.6) Reconstruction of the missing structural vault portion.

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<th>mq</th>
<th>4,45</th>
<th>1,023,50</th>
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<tbody>
<tr>
<td>2.7)</td>
<td>Filling in lightweight material to the extrados of the new reconstructed parts; cast concrete (4 cm) with welded steel net (mesh 10x10 cm) and construction of a flooring, leaving in high or low relief the parts of vault with suspensurae (Fig. 16).</td>
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<thead>
<tr>
<th></th>
<th>mc</th>
<th>2,79</th>
<th>368,28</th>
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<tr>
<td></td>
<td>mq</td>
<td>2,225</td>
<td>55,62</td>
</tr>
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<td></td>
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<td>2,225</td>
<td>77,87</td>
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<th></th>
<th>[€/m³]</th>
<th>2,213,72</th>
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<td>[€]</td>
<td>82,505,3</td>
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Fig. 17 - Third solution: bridge crane scheme (a); reconstruction of vault.
Third solution

3) Repositioning of the collapsed vault blocks, integration of the missing parts with new masonry and construction of a steel bridge-like deck (not isolated) at the extrados of the barrel vault to which the underlying structures are eventually hung (Figs. 13, 17).

3.1) Integration of the perimeter walls (tuff, brick and travertine) of the gallery, up to the maximum height of the vault extrados: this height is deduced from two points in which the vault is still in the original quota (Fig. 13a,b). If necessary, the perimeter walls are shaped to create the impost of the vault. On the north-western side (masonry blocks of tuff and travertine), where the longitudinal access openings to the adjacent Domus Augusto’s rooms can be found, the flat arches above such openings will be rebuilt, at their original impost quota.

3.2) Consolidation of the vault blocks (for example with injections) to improve their mechanical properties and to ensure that – during the lifting and handling stages - they will not undergo any damage.

3.3) Installation of the longitudinal (assuming HEA1000 = 272 kg/m) and transversal beams (HEA 500 = 155 kg/m) of the steel deck (including the bracings), by means of the crane (Fig. 17b).

3.4) Assemblage of the bridge crane and its positioning by crane (Fig. 17a).

3.5) Performing the following operations, proceeding by "modules":
3.5.1) lifting and positioning of the first block of the current module;
3.5.2) the block is fixed by tie rods to the transversal beams of the steel bridge-like deck (Fig. 17a);
3.5.3) the bridge crane is moved on the possible second block of the same module;

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<th>u. m.</th>
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<th>quantity</th>
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<tbody>
<tr>
<td>3.1</td>
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<td>3.35</td>
<td>544</td>
<td>1.822,40</td>
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<td>3.3</td>
<td>kg</td>
<td>kg</td>
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<td>14.000,0</td>
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<td>3.5</td>
<td>31,00</td>
<td>5,05</td>
<td>156,00</td>
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Proceedings of the 5th International Conference on Integrity-Reliability-Failure

3.5.4) lifting, positioning and fixing of the second block (if it exists) of the current module;  
3.5.5) the steel beams of the previous intervention are removed and the relevant brick walls demolished;  
3.5.6) construction of the arch-centering;  
3.5.7) predisposition of the tie rods that will sustain the parts to be rebuilt;  
3.5.8) reconstruction of the missing “structural” vault portion;  
3.5.9) the arch-centering is disassembled;  
3.5.10) installation of the tie rods for the parts to be rebuilt;  
3.5.11) moving to the next “module”.

3.6) The bridge crane is disassembled, after every block has been correctly placed.

3.7) Construction of a floor with corrugated steel sheet and reinforced concrete slab: note that the beams depth is such as to leave a space that allows to preserve the suspensurae (Fig. 17b)

3.8) The bridge crane is disassembled, after every block has been correctly placed.

Fourth solution

4) Repositioning of the collapsed vault blocks, integration of the missing parts with new masonry and construction of a steel bridge-like deck (isolated) at the extrados of the barrel vault to which the underlying structures are eventually hung (Figs. 13, 18).

4.1) Integration of the perimeter walls (tuff, brick and travertine) of the gallery, up to the maximum height of the vault extrados: this height is obtained by two points in which the vault is still in the original quota (Fig. 13a,b). If necessary, the perimeter walls are shaped to create the impost of the vault.  
On the north-western side (masonry blocks of tuff and travertine), where the longitudinal access openings to the adjacent Domus Augusto’s rooms can be found, the flat arches above such openings will be rebuilt, at their original impost quota.

4.2) Definition and identification of the supports (at least 4) of the deck on which to place the seismic isolators (Fig. 18a).

4.3) Installation of seismic isolators

4.4) Consolidation of the vault blocks (for example with injections) to improve their mechanical properties and to ensure that – during the lifting stages - they will not undergo any damage.

4.5) Installation of the longitudinal (assuming HEA1000 = 272kg/m) and transversals beams (HEA 500 = 155kg/m) of the steel deck (including the bracings), by means of the crane.

4.6) Assemblage of the bridge crane and its positioning by crane.

4.7) Performing the following operations, proceeding by ”modules”:

4.6.1) lifting and positioning of the first block of the current module;  
4.6.2) the block is fixed by tie rods to the transversal beams of the steel bridge (Fig. 18b);  
4.6.3) the bridge crane is moved on the possible second block of the same module;  
4.6.4) lifting, positioning and fixing of the second block (if it exists) in the current module;  
4.6.5) the steel beams of the previous intervention are removed and the relevant brick walls demolished;  
4.6.6) construction of the arch-centering;  
4.6.7) reconstruction of the missing “structural” vault portion (the pour);  
4.6.8) the arch-centering is disassembled;
4.6.9) installation of the tie rods for the parts to be rebuilt;

4.6.10) moving to the next “module”.

4.8) Construction of the necessary joints to accommodate the seismic displacements (Fig. 18a, b).

4.9) Construction of a floor with corrugated steel sheet and reinforced concrete slab: note that the beams depth is such as to leave a space that allows to preserve the suspensurae (Fig. 18b)

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<th>m^2</th>
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<tr>
<td>49,69</td>
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<tr>
<td>35,00</td>
<td>4,45</td>
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<td>538,971,1</td>
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**Fifth solution**

5) Construction of a bridge-like steel truss deck, by means of prefabricated modules, whose cross-section is such as to recreate the same original intrados profile. Subsequent processing of the blocks with cutting of the cortical parts, both 1) at the intrados (curvilinear), and 2) intrados (flat) in portions to be fastened at the steel truss deck, at the this latter’s intrados and extrados, respectively. (Those portions could be of dimensions such as to be handled by naked hand, that is without crane).

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5.1) Numeration and accurate survey of the current position of the collapsed vault blocks.

5.2) Integration of the perimeter walls (tuff, brick and travertine) of the gallery, up to the maximum height of the vault extrados: this height is deduced from two points in which the vault is still in the original quota (Fig. 13a,b). If necessary, the perimeter walls are shaped to create the impost of the vault.

5.3) Consolidation of the vault blocks (for example with injections) to improve their mechanical properties and to ensure that – during the subsequent lifting and handling stages – they will not undergo any damage.

5.4) The vault blocks are lifted by crane, positioned outside of the Gallery, and stored in a nearby outdoor area.

5.5) Cutting of the cortical parts of the vault blocks by grinding machine: 1) at the intrados (curvilinear portions of the structural arch), and 2) at the extrados (supported filling including the so-called “suspensurae”) (Fig. 19).

5.6) Transportation to the construction site of all the modules of the steel bridge-like truss deck.

5.7) Positioning in place by crane and assemblage of the steel truss modules (assumed indicatively 1m deep). Steel truss module (U140 = 16kg/m; L20x20 = 1,14kg/m; U100 = 10,60kg/m) (Fig. 19).

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<tr>
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<tr>
<td>3,35</td>
<td>659,20</td>
<td>30,16</td>
<td>2.208,32</td>
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<tr>
<td>3,35</td>
<td>473,73</td>
<td>101,03</td>
<td>1.586,99</td>
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5.8) Removal of the elements composing the previous intervention. The steel beams are cut flush against the wall surface so that the left part of these will remain “incorporated” in the masonry (historical memory of the previous intervention) (Fig. 13b); transportation of end products in landfill.

5.9) Positioning in place and fastening to the steel truss deck of the cortical elements (both intrados and curvilinear and extrados and flat). Such operations could be carried out, at the intrados, by naked hands, per small portions while, at the extrados, per larger portions, handled by the crane. Cortical extrados portions are positioned in such a way to
result in high-relief with respect to the surrounding practicable floor.

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<td>mq</td>
<td>35.00</td>
<td>4.45</td>
<td>155.75</td>
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<td>[€/ml]</td>
<td>4.971.88</td>
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<td>[€]</td>
<td>185.301.9</td>
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Fig. 19 - Fifth solution: steel truss deck, with fastened cortical portion of the original barrel vault.

**SELECTION OF THE FINAL SOLUTION**

In the previous section, all the contemplated retrofit strategies were described in detail. Advantages and disadvantages of those solutions are discussed hereinafter.

The first hypothesis substantially envisages the following phases: 1) positioning of a bridge crane, 2) repositioning of the blocks, 3) building the wood plank arch-centering, 4) building (casting) of the vault, 4) construction of the steel deck at the vault extrados. This solution presents some aspects difficult to address properly: 1) after building the wooden plank arch-centering, since the bridge crane should be still in place, it would heavily reduce the freedom of movement at the extrados during the construction of the new portions of the vault, 2) the resulting structure would be composed of old and new parts whose interaction would be extremely delicate and difficult to handle, from a safety calculations standpoint, due to the inevitable difference in mechanical properties, 3) the expeditious calculations herein presented showed that the vault was ill conceived so that it is not reasonable to re-built, faithfully to its original features, a structure that was already affected by huge defects, 4) it is very expensive due to the hiring of both crane and bridge crane.

The second hypothesis aims at re-building the vault reducing the local operations by 1) initially moving the blocks outside the gallery perimeter by crane, 2) building the wood plank arch-centering, 3) building the missing parts of the gallery. This solution, even though less expensive than the first one, due to the absence of the bridge crane hiring, still maintains the safety-related issues. In fact, we would realize a structure that was evidently deficient, by also pretending to rely on the interaction between old masonry and new masonry. This is even more pretentious if we remark the heterogeneity of the masonry material itself, even more if it is ancient. With respect to the previous one, this solution presents, anyway, the advantage of
reduced costs. Even if, in the present work, for the sake of brevity, the interventions necessary to make both the vault and its supporting walls earthquake-resistant were not accounted for.

The third hypothesis envisages: 1) the positioning of the bridge crane, 2) building of the wood plank arch-centering, 3) installation of the steel braces that will support the vault, 4) realization of the missing parts of the vault that will remain hung at the steel deck realized at the vault extrados. This solution eliminates the issues related to the interaction between old and new masonry since the vault would remain hung at the steel deck, but maintains the feasibility problems related to the interaction of constructive phases that affect the first solution. Among the advantages of this solution there is also the reversibility (Brandi 1977). In fact, since the new parts are hung at the steel deck, they could be removed.

The fourth solution envisages the seismic isolation of steel deck to which the vault should be hung by steel rods. This solution is unfeasible for several reasons: 1) the steel deck would need point-wise supports (four) with high local stress concentration that would require heavy interventions on the supporting lateral walls, and 2) large portions of the lateral walls should be cut in order to accommodate the lateral displacements that the steel deck would undergo during an earthquake. Such solution would result too invasive, and not in agreement with the restoration philosophy currently accepted. In fact, the full seismic rehabilitation strategy, allowed by the 1981 Ministerial Decree (D.M.LL.PP 1981), has been progressively abandoned in favor of the less invasive seismic amelioration strategy, which is the intervention design solution currently accepted in Italy for the monuments (LINEE GUIDA 2010).

The fifth solution envisages the following phases: 1) moving the blocks outside of the gallery perimeter, 2) positioning of the prefabricated steel truss modules on the longitudinal supporting walls and their assemblage on site, 3) cutting of the cortical part of the blocks, both intrados (curvilinear) and extrados (flat), 4) positioning and fastening of the cortical parts, whose dimensions may be such as to allow bare hands movement, 5) construction of the practicable floor at the extrados. Many are the advantages that seem to characterize this solution, among which: 1) reversibility, 2) minimum disturbance to the supporting walls, due to the continuous support, as opposed to the point-wise one of the fourth solution, for instance, 3) relative inexpensiveness, due to the possibility of prefabrication of the deck in modules, 4) improving safety by also connecting the two longitudinal walls thus improving their behavior against seismic actions orthogonal to their longitudinal development. Moreover, other materials, lighter and less vulnerable to corrosion than steel could be adopted, such as Aluminum or Fiber Reinforce Polymers (FRP), respectively.

CONCLUSIONS

This paper presented a preliminary study of possible alternative retrofitting strategies of a collapsed vault placed in the central archeological area of Rome, in Italy. It is a Gallery placed inside the famous Augusto’s House area. For not documented reasons, this gallery must have undergone a collapse, in an unknown time of history. Subsequently, in the second half of the twentieth century, it was retrofitted by a complex intervention based on the use of wooden struts, steel beams, and squat masonry blocks. This intervention, however, presents many limits.

By means of simple mechanical models, the safety of the vault, considered in its original features, showed that it was characterized by design defect that made it vulnerable to seismic loads. Thus, it may have collapsed due to an earthquake.
The fifth, among the retrofitting design hypotheses taken into consideration, resulted the most suitable one, in terms of a) reversibility, b) expensiveness, c) disturbance brought to the existing surrounding structures, d) safety. This solution envisages 1) the construction of a steel truss deck, whose shape aims at reproducing the same intrados profile as the original gallery, continuously supported along the lateral walls, and 2) the fastening of the cortical portions only, of the collapsed blocks, to the truss. This solution, also reduces the seismic vulnerability of both vault itself and supporting walls, by dramatically reducing the masses involved.

REFERENCES


