THE STRUCTURAL DESIGN OF THE GREAT HALL OF TRAJAN’S MARKETS

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Abstract
We present a systematic study of the structural behavior of the Great Hall of Trajan’s Markets under static gravitational loads, based on linear elastic Finite Element stress analysis. Several three-dimensional Finite Element models derived from a computational solid model of the Great Hall are used to explore the deformation patterns and the stress fields under the assumptions of fully-hardened opus caementicium and of different mechanical conditions at the interface of the supporting travertine blocks. The contributions to static stability of the vault by the lateral contrasting arches and by the transverse shear walls are evaluated by analyzing reduced models in which either the arch, or the wall, or both have been eliminated. Computational results are validated against the present state of the Great Hall by considering the fracture pattern of the vault, the state of the contrasting arches, and the traces of lateral clamps in the travertine blocks. The lateral arches are found to play no significant role in the static equilibrium of the vault. In contrast, the travertine blocks and the shear walls are shown to be the critical elements on which the stability of the vault hinges. The inherent weakness of the structural configuration suggests that the designer was not aware of the typical failure mode of a large cross vault in opus caementicium. The Great Hall may thus represent a critical point in the development of the understanding of structural behavior that made possible the successful design of much larger cross vaulted structures.

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1. Introduction.

This study seeks to evaluate the structural response of the Great Hall of the Markets of Trajan under static dead loads (self-weight only) with particular attention to the functionality of the system of lateral contrasting arches, supporting travertine corbels, and transverse shear walls, which characterizes the structural skeleton of the hall. We approach this study with the assumption that the mechanics of fully-hardened Roman concrete, like its modern successor, can be modeled with adequate engineering approximation as a deformable elastic solid. Thus, following well-established procedures from current civil engineering practice, the evaluation of structural behavior can be conducted with the help of modern computer based numerical tools for stress analysis, such as the Finite Element method. As we shall see, this approach not only allows for the accurate modeling of the Great Hall as a structural unity, but also provides the means to evaluate the individual contribution to the static response of a particular structural element under consideration. The present study, the first of a series dedicated to the Great Hall, is part of an interdisciplinary research on the engineering design of concrete Roman vaults conducted at the University of Rochester, Rochester NY, in collaboration with the Museums of the Imperial Forums and the University “La Sapienza” in Rome. Work currently in progress addresses specific issues related to the static stability of the monument under damaged conditions as well as its response to seismic loads.

The Great Hall occupies a preeminent position within Trajan’s Markets, the imperial building complex on the Quirinal hill overlooking the Forum of Trajan in Rome (fig. 1). Built between the years 98 and 117 AD and essentially intact in all its structural elements, the hall is a vaulted rectangular space 36 m long and 8.8 m wide, constructed entirely in Roman Pozzolanic concrete (opus caementicium). The vault itself was built as a single concrete block, flat at the extrados and with the intrados articulated into a series of six approximately equal cross vaults. The vault is supported vertically by fourteen travertine piers, each consisting of two superimposed elements: a projecting corbel above a prismatic block partially embedded into a concrete wall. These walls are set transversely to the long axis of the hall, following a nearly symmetric pattern. Above each pier and on the plane of the corresponding transverse wall, a lateral concrete arch horizontally connects the top of the vault to the vertical extension of the wall (fig. 2).
Somewhat surprisingly, although the Great Hall has been studied extensively and its importance in the history of Roman concrete vaulting recognized since being brought back to its original state by the 1926-1934 restorations\(^1\), a complete and systematic engineering investigation of the monument based on quantitative analysis has never been published. Giovannoni was the first to apply engineering considerations to the structure of the Great Hall.\(^2\) Writing before the monument had been liberated from the accretions that had altered its appearance to the point of making the original structural skeleton completely invisible, he based his observations on a series of Renaissance drawings. Because of their shape and position, Giovannoni identifies the lateral arches as perfect examples of flying buttresses, functionally identical to those found in medieval gothic architecture. This identification is made in the context of a study of Roman prototypes of contrasting arches and flying buttresses, in which Giovannoni draws a direct analogy between the structural system of transverse walls and contrasting arches found in the Frigidarium of the Baths of Diocletian and the Basilica of Maxentius, and the system of transverse walls and flying buttresses of the Great Hall. These initial considerations were repeated and expanded in a later study published while the restoration of the Great Hall was in progress.\(^3\) Here Giovannoni applies the static graphic approach on a transverse section of the hall to show that the vault thrust line does not follow the intrados of the vault, but, due to presence of the lateral arch, crosses internally to the projecting corbel and then remains inside the transverse wall. Although based on inaccurate dimensions – the height of the corbel with respect to the lateral shear wall is clearly wrong – this analysis is historically important since it remains to the present the only one ever published on the Great Hall. As such it provided the only quantitative basis on which the functional role of the lateral arches and, implicitly, the structural behavior of the concrete vault could be evaluated.

A different structural interpretation was put forth by MacDonald. In discussing the lateral arches he rejects Giovannoni’s interpretation and asserts that “…their position and the structural nature of the building preclude calling them flying buttresses. The near-monolithic

\(^1\) For early studies of the Market of Trajan see RICCI 1929; LUGLI 1930; BOETHIUS 1931; PERNIER 1938. The architectural innovation represented by the Great Hall is described in WARD-PERKINS 1981. More recently, a series of in-depth archaeological studies of the Great Hall have shed additional light upon aspects ranging from the construction (LANCASTER 2000), to the definition of internal components (BIANCHINI 1991, BIANCHINI AND VITTI 2003), and their qualitative function as a structural whole (UNGARO 2003).

\(^2\) GIOVANNONI 1913, p. 287; GIOVANNONI 1925, p. 63.

\(^3\) GIOVANNONI 1929, p. 237; GIOVANNONI 1938, p. 307.
quality of the vault is such that once the concrete had cured the arches would be brought into play very little and probably not at all.” MacDonald instead proposes that the arches served a constructional purpose, after which “… they stand ready to give a certain lateral support should the building move.” The contrasting arches “… also load the main vault somewhat toward its main longitudinal center line. This load is difficult to measure accurately, but it exists, and it helps give stability to the whole.”4 These observations by MacDonald represent an important contribution, since they consider the function of the contrasting arches as being largely dependent upon their position within the geometry of the vault and upon the mechanical behavior of the material of the vault.

In a series of recent studies dedicated to concrete vaulted construction, Lancaster relates the necessity of horizontal buttressing for the Great Hall to the use of travertine blocks to support the vault.5 Essentially following Giovannoni’s interpretation, the arches are described as early precursors of flying buttresses designed to convey the lateral thrusts produced by the cross vaults into the extension of the transverse walls. She further suggests that “…lateral thrusts could have developed from cracking in the vaults, creep in the concrete, or even wind pressure.”6 Lancaster finds an indication of the thrust transmitted by the arches in the outward tilt of the western wall of the Great Hall, which she interprets as likely due to plastic deformation induced in the concrete of the transverse walls.7

Finally, in a comprehensive study of building engineering and construction, Addis continues to interpret the arches as flying buttresses but provides only a qualitative sketch showing vault thrusts flowing through the arches into the shear walls.8

2. Objectives

In the present work the Great Hall is the focus of a series of numerical analyses simulating its structural behavior under static gravitational loading and with the assumption of fully-hardened concrete. The study aims at understanding the mechanics of deformation and of possible failure of the vault and of its supporting system under static conditions. The specific

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4 MacDonald 1965; pp. 87-8.
6 Lancaster 2000, pp. 775-6.
objectives are: identify locations subjected to elevated tensile or compressive stresses and thus at risk for damage; examine the functionality of the lateral arches and of the transverse shear walls as contrasting elements necessary for the static stability of the vault; and, finally, attempt a comprehensive evaluation of the structural design of the Great Hall.

3. Methods

The analysis method consists of a series of three-dimensional linear Finite Element models that represent the mechanical behavior of the Great Hall, either in its entirety or as particular structural subsets. The Finite Element analysis method is employed here for two principal reasons. First, it is the standard computational tool in current engineering practice for the design and analysis of concrete structures, both reinforced and un-reinforced.9 As such, it is able to determine with reasonable accuracy the complete stress state for complex three-dimensional constructions like the Great Hall. Second, it readily permits the subtraction or isolation of various structural elements, as a means towards evaluating their role within the support scheme of the whole construction. The Finite Element models are subjected to the loading and support conditions that simulate those experienced by the structure disarmed from its centering formwork and with its concrete assumed to be fully-hardened. The analysis of these models provides the deformed configuration of the structure together with the related stress and strain fields. For analysis verification purposes, these results are then compared against the observable physical condition of the structure. As discussed below, based on this approach, the dominant mechanical behavior of the structure is understood to be a downwards deformation of the intrados of the main vault accompanied by an inward rotation of the upper travertine blocks of the support piers, which themselves are the primary determinants of the structural stability of the vault. Concurrently, the external contrasting arches are found not to contribute to the supporting of the main vault, while the transverse

9 From its inception in the 1960’s the Finite Element method has been applied to the stress analysis of concrete structures, see, for example, ZIENKIEWICZ AND TAYLOR 2005. For a discussion on the applicability to Roman concrete structures, see SAMUELLI FERRETTI 2005. MARK AND HUTCHINSON 1986, Tosi 1997, Croci 1998, and Samuelli Ferretti 2005 provide examples of systematic application of the method to the analysis of major Roman monuments in opus caementicium.
walls insure the stability of the piers and, therefore, are crucial for the static stability of the entire vault.

3.1 Model configuration: geometry

All Finite Element models in this study are based on a three-dimensional computational solid model created in PRO/ENGINEER. The dimensions of the solid model are obtained from a survey of the entire complex of Trajan’s Markets conducted by La Sovraintendenza BB.CC. del Comune di Roma. Several simplifications are introduced in order to reduce the geometrical complexity of the model while still preserving all details relevant to the static behavior of the structure. Symmetry is assumed across the plane of the longitudinal axis of the Great Hall, with the only exception being both levels of the northern-most bay. To isolate the Great Hall from the rest of the Markets complex, a boundary is defined along the southern-most end of the hall (fig. 1). No structural elements south of this are represented in the model, and any stabilizing effects contributed by the removed connection are neglected.

The solid model of the detached Great Hall needs to capture all the features of structural significance – the presumed structural skeleton. Accordingly, all components within the isolated area of interest that contribute appreciably to either the structure’s weight or the load path along which the weight discharges to the foundation are included\(^\text{10}\). The primary elements are the main vault, the supporting piers, the transverse walls, and the contrasting arches. As the study is concerned with the building in its original working conditions, the vault intrados is reconstructed to its presumed original shape (fig. 2). The additional level atop the eastern second level rooms is excluded, as it does not contribute to the static support of the vault. Similarly, the level beneath the western rooms is not represented in order to simplify the model. Instead, a uniform foundation at the ground level of the Great Hall is assumed for all transverse walls, ignoring the potential differential support condition between the western sector, which is carried on the concrete walls of the excluded lower level, and the eastern sector and main hall, directly built on concrete foundations. The resulting solid model is shown in fig. 3.

\(^{10}\) The Great Hall model used in this study does not include projecting brick arches that – according to Renaissance representation of the Great Hall – spanned the intrados in correspondence of each set of corbels, but for which there is no archaeological evidence (BIANCHINI 1991). Their possible structural contribution requires nonlinear modeling and will be examined in a future study.
3.2 Model configuration: materials

The validity of the Finite Element model is largely dependent upon the mechanical characterization of the structural material. In the case of the Great Hall, this is Roman Pozzolanic concrete (opus caementicium) with brick facing limited essentially to the vertical walls and the lower part of the piers. The concrete aggregate of the cross vaults consists exclusively of tuff fragments (tufo giallo della via Tiberina)\textsuperscript{11} arranged in horizontal layers. A layer of opus spicatum and of opus signinum are present in the extrados of the vault. As indicated earlier, travertine limestone is used for the corbels and supporting blocks. In order to reduce the complexity of the modeling task, the entire structure is assumed to consist solely of opus caementicium. Thus, ignoring the difference in material behavior, the model represents the travertine support piers as concrete blocks, forming a structural continuum with the vault and the transverse walls. Also, the brick facing is not separately represented within the model; instead it is incorporated as an additional thickness of the concrete walls, under the assumption that its response is not appreciably different from that of the concrete core.

Experimental studies conducted by Samuelli Ferretti and coworkers on the mechanical response of opus caementicium to various type of loading conditions have shown that the material behaves in a manner qualitatively similar to modern concrete.\textsuperscript{12} Loaded in compression, the material exhibits nearly elastic deformations up to the strength limit followed by a pseudo plastic behavior characterized by permanent deformations and gradual loss of load bearing capability. Micro-cracking in the cement paste and separation at the cement-aggregate interface appear to have a dominant role in determining the compressive (crushing) strength of the material. A similar behavior is registered in tension, but in this case the strength is approximately one tenth of the compressive limit. As the tensile stress reaches the strength limit, the material fractures on a surface perpendicular to the direction of the tensile stress. As for Finite Element modeling of modern concrete structures, Roman concrete can be reasonably approximated as a linear elastic material, as long as the compressive and tensile stresses remain below the strength of the material. This is true if the analysis is limited to the

\textsuperscript{11} \textsc{Lancaster} 2000; p. 776.
\textsuperscript{12} \textsc{Samueelli Ferretti} 1995a, 1995b, 1997 and \textsc{Perno} 1997 provide extensive mechanical data (e.g. compressive and tensile strength, stress-strain curves, etc.) on opus caementicium and its components. \textsc{Lamprecht} 1984 and \textsc{Oleson et al.} 2004 contribute compressive strength values, but are of limited applicability to the present study.
determination of stress distributions under normal working conditions – such as, for the present case, under gravitational loads. Based on the mechanical testing by Samuelli Ferretti of samples of *opus caementicium* of similar composition taken from the Basilica of Maxentius, the material in the Great Hall is characterized as a linear elastic solid with Young’s modulus $E = 3 \text{ GPa}$, mass density $\rho = 1500 \text{ kg/m}^3$, and Poisson’s ratio $\nu = 0.2$. As indicated by Samuelli Ferretti, the compressive strength can be safely assumed to be between 4.0 and 5.0 MPa, while a reasonable estimate for the tensile strength is between 0.4 and 0.5 MPa. Implicit in the assumption of linear elastic behavior for the type of structure under investigation is the requirement that only very small deformations occur due to the applied load. Accordingly, the validity of the Finite Element results must be verified by comparing the magnitude of the computed displacements with the characteristic dimensions of the structure.

### 3.3 Finite Element meshes

The final stage in preparing the numerical models is the creation and characterization of the Finite Element meshes. Given the objectives of this investigation, several different meshes are used, though each is created in a similar manner. First, a complete instance or a section of the solid model of the Great Hall is imported into ABAQUS CAE for Finite Element preprocessing, wherein the various analysis parameters are defined. In the initial stage of the investigation, focused on the mechanics of a typical cross section, an internal or external transverse section of the structure is cut from the entire model and used for the analysis (fig. 4.) Later on, the analytical models make use of the geometry of the entire Great Hall. With the help of the auto-meshing utilities available in the CAE preprocessor, the imported solid geometry is partitioned into a collection of interconnected tetrahedral elements – the mesh – that fit together to closely approximate the solid being analyzed. The number of elements and their relative size within the mesh depends upon the desired accuracy in representing the geometry of the structure, the loading and support conditions, and the computed displacement and stress fields. Quadratic tetrahedral elements with linear elastic material behavior are used throughout this study because of their excellent resolution capability even with relatively coarse meshes. In order to model the mechanics of *opus caementicium* seeking static equilibrium under gravitational loads, the elastic material parameters defined in Section 3.2 and the gravitational acceleration are assigned to each tetrahedral element in the mesh. Finally, the support action provided by the foundations, assumed perfectly rigid and with no
differential settlement, is represented by the addition of fixed boundary conditions, i.e., zero displacements in all directions, to the surfaces of the model located on the ground level of the Great Hall. Once preprocessing is completed, a linear solution procedure in ABAQUS/Standard is used to compute the statically deformed configuration that results from the applied gravity loading.

4. Models and results

The results from the sequence of linear Finite Element analyses are examined to first ascertain the overall mechanical behavior of the monument, and subsequently determine the structural role of individual components. The following sections detail how each Finite Element analysis is configured, the motivation behind its usage, and the significance of the results it produces. The results considered are in the form of displacements (deformed shape) and stress distributions. The deformed shape shows how the structure modifies its configuration to resist the applied loads. Thus, computed displacements must be verified for consistency with all imposed loading and support conditions. This also insures that no input errors were introduced during preparation of the model. In addition, the analyst must check that the deformations are small enough to justify the assumptions of linear elastic behavior. In the figures that follow, due to the relatively small magnitude of the displacements, the deformation patterns are considerably magnified in order to underline the salient features of the mechanical response. Stress distributions – shown as color coded bands in the figures – reveal how the internal forces generated by the applied loads flow through the structure. Of primary importance are the regions where the maximum stresses are tensile, since these are areas where material damage (i.e., fracture initiation) could occur, given the comparative weakness of Roman concrete in tension. Similarly, regions of high compressive stresses must be inspected to identify possible crushing conditions.

4.1 Interior and exterior Symmetry Sections – Analysis 1

The first analysis set uses interior and exterior transverse modular sections – fig. 4(a) and (b), respectively – to obtain the baseline static response of the Great Hall under gravitational loads. Following standard procedures in Finite Element stress analysis, the model is cut along planes of geometrical and mechanical symmetry and the desired (reduced) section is selected for
meshing. Appropriate kinematic conditions are applied on the planes of symmetry to simulate the mechanical effect of the removed portion of the solid. The exterior section is used in order to evaluate the effect that an unconstrained (external) side has on the structural response of the vault.

The displacement results for the interior section, magnified in fig. 5, show that the deformation mechanism of the main vault consists of two superimposed motions: a vertical downward translation due to the compression exerted on the transverse walls and a flexural (bending) deformation with characteristic sagging of the extrados. The maximum downward vertical displacement reaches 3 mm at point A, approximately half of which is due to bending. The sagging at the top is accompanied by an outward lateral expansion just above the springing of the vault, with maximum lateral deformation of 0.5 mm at B. Notice that along the edge of the extrados (point C) the horizontal component of the deformation turns inward. The lateral arches are bent downward, without any appreciable change of length along the axis. Nearly identical displacements are computed for the exterior section. The maximum displacement – 3 mm over the 8.5 m internal span of the vault – is well within the boundary of the assumed linear elastic behavior.

The computed stress distributions indicate the presence of tensile stresses at the intrados due to the flexural deformation of the vault, with bands of elevated stresses near the crown, in correspondence to maximum bending conditions (fig. 6). Nuclei of equally elevated tensile stresses, also due to bending, are present at the end sections of the lateral arches. Maximum tensile values in the vault and the lateral arches reach 0.25 MPa and are directed orthogonally to longitudinal plane of symmetry, i.e., along the x axis in the figure. Maximum compressive stresses, not shown, are almost everywhere below 0.6 MPa, with local peaks of 1.0 MPa. Similar stress distributions are computed for the exterior section model, indicating that the effects brought about by the unconstrained end are only marginally significant in terms of the overall static structural response in the vault.

4.2 Model with Removed Contrasting Arches – Analysis 2

A single, but significant, change is made to the interior section for the second analysis model. In order to evaluate its structural role in supporting the main vault, the lateral contrasting arch is removed from the solid model. The modified interior section is meshed in an identical
manner to the previous Finite Element models. All other parameters (material definition, symmetry and support conditions, gravitational loads) remain the same, allowing for a direct comparison of the results between models with and without the contrasting arch.

Analysis 2 shows that both deformations and stresses are essentially unaffected by the removal of the contrasting arch. In fact, the maximum deformation at the crown of the vault has exactly the same value as computed in Analysis 1, while the peak in tensile stresses at the center of the vault is actually reduced slightly (about 5%). Missing the arch, the nuclei of high tensile stresses located at the end sections of the contrasting arch are also eliminated. A direct comparison of the maximum tensile stresses in the vault with and without lateral arch (fig. 7) confirms that the arches do not affect in any substantial manner the distribution of internal forces acting on the vault.

4.3 *Motion of the Travertine Blocks – Analysis 3*

The effect of a relative motion between the upper and lower travertine blocks on the structural response of the vault is now taken into account. The pier configuration, with the corbel projecting out from the lower block, suggests the possibility that the upper block may rigidly rotate and slide on the lower one, while the structure is undergoing elastic deformations due to the gravitational load. Clearly, friction between the two blocks plays a fundamental role in this mechanism and should be included in the Finite Element model. However, within the confines of the linear analysis approach taken in the present study, this type of relative motion can only be approximated by introducing a sliding frictionless contact between the blocks. To create the appropriate model, the vault is detached from the base along a horizontal cutting plane located at the interface between the corbel and the lower travertine block (fig. 8). Notice that the cut extends to the transverse walls. The detached vault is then meshed as in the previous analyses and either a rolling or a fully fixed support condition is applied on the lower face of each corbel creating two different Finite Element models. With the roller support the corbel is allowed to slide horizontally without friction, while the fully fixed support essentially reproduces the conditions at the pier used in all previous analyses. The remaining support condition on the cut surface of each transverse wall is set to fully fixed in both analyses.

In contrast with Analysis 1, the vault displacements are now due to bending only and are considerably affected by the support conditions, since sliding of the blocks markedly increases
the deformability of the structure under gravitational loads (fig. 9, top). In comparison with the fully fixed case, sliding results in a 200% higher sag at the crown with 2.0 mm lateral translation of the blocks. The stresses follow identical patterns, but with dramatic differences in magnitude (fig. 10). While for the fixed case the distribution of tensile stresses at the intrados is essentially the same as in Analysis 1, sliding increases the peak tensile stresses by 200%. This major variation in the mechanical response indicates that friction at the interface between the travertine blocks is a critical factor for the static stability of the vault.

4.4 Model with Lateral Support Walls Removed - Analysis 4

The previous results suggest that the vault develops significant horizontal thrusts at the level of the travertine blocks, thrusts that must be opposed by the transverse concrete walls located below the blocks. To better understand the role of these walls as the primary restraint against horizontal forces, a new model is created with the transverse walls removed by cutting along the external lateral surfaces of the vault. The resulting mesh consists only of the main vault with supporting piers extended to the ground level, modeled as a continuous concrete structure (fig. 11).

The computed deformed shape (fig. 12) clearly shows the “opening” mechanism of the vault, characterized by the large bending deformations of the vault and the piers. The lateral displacement at the level of the travertine blocks, previously opposed by the transverse walls, is now of the same order of magnitude of the maximum vertical displacement of the vault. The maximum tensile stresses developed in the vault are over 200% higher than those computed with the transverse walls in place.

5. Critical interpretation of results

The validity of the results is corroborated by physical evidence observable in the Great Hall, the most prominent being the longitudinal fracture at the crown of the intrados of the main vault, revealed during the 1926-1934 restorations (fig. 13) and whose traces are still visible today after the 2005-2007 cleaning of the vault. All Finite Element models predict a band of elevated tensile stresses on the intrados at the crown spanning the entire length of the vault, with peak values of 0.25 MPa and directed perpendicular to the plane of longitudinal symmetry (fig.s 6, 7, and 10). The magnitude of these stresses is not appreciably affected by the removal of the
lateral arches, but is altered dramatically by the sliding of the travertine blocks, reaching levels in excess of 0.65 MPa (fig. 10). The direction of the maximum stresses is insensitive to these changes. These results can be summed up as follows: stresses at the crown of the intrados are dangerously close to the estimated tensile strength of the *opus caementicum* (0.4–0.5 MPa); even minor sliding of the travertine piers can indeed generate stresses exceeding the strength level and cause a fracture to develop in the plane of longitudinal symmetry. Direct observation of the Great Hall confirms that the existing longitudinal fracture coincides in location and orientation with the prediction of the model. In turn, the evidence validates the bending deformation of the vault, which causes the tensile stresses at the intrados.

The analysis results also predict the existence of nuclei of elevated tensile stresses (0.25 MPa) in the end sections of the lateral arches, due to bending deformations. As indicated by the large rotations of the end sections visible in fig. 9, sliding of the travertine blocks increases substantially the bending of the arches and causes the stresses to rise above the strength limit. Thus, it is logical to expect that fractures will develop at these sections, possibly leading to the total collapse of some arches. Here again, physical evidence supports the findings of the analyses. Of the thirteen arches existing today, only few are original, the others being reconstructions that replace collapsed arches. Furthermore, in the concrete core of one of the original arches, an extensive fracture, located at an end section abutting the vault and oriented as predicted by the analysis, was clearly visible before being hidden by a new brick coating during the 2005-2007 restoration (fig. 14).

Analysis 1 and 2 prove that the lateral arches do not perform any appreciable contrasting function in resisting the horizontal thrust produced by the vault under static conditions. This point is worth special consideration given the pervasive nature, from Giovannoni’s 1913 study onward, of the notion that these are contrasting elements necessary to convey horizontal forces. Figures 5, 7 and 15 prove the lack of functionality. There is no appreciable alteration of the deformed state of the vault due to removal of the arch. Therefore, the flow of internal forces does not depend on the presence of the arch. More precisely, no horizontal (axial) force is transmitted through the arch – as required in a true contrasting action – simply because no horizontal force is needed for the static stability of the vault at the point of attachment of the arch. In fact, well below the arch, this stabilizing action is provided by the transverse shear

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13 VITTI 2005.
walls, as clearly demonstrated in fig. 15, in which the lethality of wall removal is contrasted with the lack of effect induced by the absence of the arch. To stress this point even further, figs 12 and 15 taken together confirm that the lateral arch cannot overcome the instability condition caused by removal of the transverse wall.

The non-functionality of the contrasting arches and the low setting of the shear walls force the travertine blocks to assume an additional – and likely unintended – mechanical role. In addition to the vertical load, the entire horizontal thrust necessary to contain the bending of the vault must travel through the travertine blocks. In fact, the transmissibility of this force depends upon the contact conditions between the corbel and the lower block. Analysis 3 proves the case by testing two alternative conditions: full adherence between the blocks with vertical and horizontal force transmission, versus perfectly frictionless sliding on the horizontal plane with only the vertical force transmitted. Since free sliding causes unacceptable deformations and stresses (figs 9 and 10), it must be prevented by developing a horizontal reaction. Hence the new – and crucial - mechanical role of the travertine blocks. In reality, the fixed/sliding mechanism allowed by linear Finite Element analysis cannot model with the necessary accuracy the hypothesis of relative motion between the blocks, especially if the effect of the corbel rotating over the lower block needs to be included. Physical evidence on the blocks – in the form of the housing of five vertical butterfly clamps sets on three sides of each pier at the interface of the travertine blocks as to prevent the inward rotation of the corbel - suggests that this rotation must have taken place.14 A complete analysis of the contact mechanics between the travertine blocks is beyond the scope of the present study and will be carried out in a subsequent study using nonlinear Finite Element models.

6. Conclusions

The results of the present study allow us to attempt a comprehensive evaluation of the structural design of the Great Hall, considering it first as an isolated project and then as an integral part of the evolution of the design philosophy of Roman concrete vaulted structures.15

The choice of low shear walls and high contrasting arches, with interposed free-standing

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15 In the following, all engineering considerations refer strictly to the original Trajanic structure, without including the alterations brought about in later ages and, obviously, not considering the structural changes introduced by modern restorations and consolidations.
travertine blocks, which together control the static stability of the cross vault, is at best problematic. The blocks are the weakest link in the structural organism because, as configured in the design of the Great Hall, they can only provide a precarious support condition to the vault. Relative motions of the blocks, due, for example, to settlement of the foundations, are likely to cause extensive fracture at the crown of the intrados. Sliding of the blocks during an earthquake may propagate the damage to the point of structural collapse. Friction between travertine surfaces – and, equally, adhesion between *opus caementicium* and travertine – is then the physical parameter controlling the stability of the configuration, arguably a poor design choice, since these surfaces must convey a sizeable horizontal force from the vault to the shear walls. In this sense, the system of butterfly clamps described earlier may be interpreted as an attempt to correct the faulty design of the support system. The lateral arch is ineffectual. Because of its position, it does not participate in the transmission of the horizontal force and, obviously, cannot prevent the relative motion of the blocks. Thus, the engineering design choice of free-standing travertine blocks and a high contrasting arch is poor. Yet, we must not disregard the fact - already noted by Giovannoni 16 - that the shear wall is correctly positioned in the transverse plane and properly sized. In fact, assuming that the blocks are not moving, the wall provides the appropriate stabilizing reaction necessary to control the deformation of the vault.

Before proceeding with the discussion of why a poor design choice was made, we need to point out that the deficiencies detected in our analysis of the Great Hall were systematically corrected in the design of successive cross vaulted structures of substantially greater – indeed, gigantic - span, such as the *Frigidarium* of the Baths of Caracalla and of the Baths of Diocletian, and the main hall of the Basilica of Maxentius. In all cases, the shear wall was extended upwards, the contrasting arch was lowered to become an extension of the shear wall, and the supporting blocks were completely encased in the *opus caementicium* of the wall. For earlier cross vaults, if they indeed existed, we do not have enough surviving physical evidence of their designs to attempt a detailed engineering analysis. Therefore it is impossible to establish exactly where the design of the Great Hall fits in the evolutionary development of concrete vaulted structures, which begins presumably in the second century B.C. with the *Porticus Aemilia* and culminates in the early fourth century with the Basilica of Maxentius.

Taking into account that the design of the Great hall is unique, i. e., no other known Roman

16 Giovannoni 1913.
structure exhibits the same combination of low shear wall, high contrasting arch, and free
standing supporting blocks, two scenarios are possible. Either the Great Hall is the first
attempt to design a free-standing cross vault in *opus caementicium* of sizeable dimensions, or it
represents a deviation from an already established design paradigm - a deviation whose
peculiarities were dictated by considerations external to structural engineering. The latter
scenario seems unlikely, since it implies that the designer intentionally selected a configuration
inherently weak and potentially catastrophic, making a technical choice which would be
difficult to reconcile with the importance of the project and the caliber of the technical staff
that must have been in charge of it. Simply stated, the choice of an inferior structural solution
is incompatible with the imperial nature of the project. On the contrary, the very notion of a
prestigious commission that required a new technical solution and resulted in the creation of a
new structural form - the cross vault - can help explain the innovative aspects and the
unexpected deficiencies of the design the Great Hall. We thus assume that the structural
designer was unaware of the mechanical implications of the design choice.

What then was the design intention? The configuration of the supports and the positioning of
the contrasting arches suggest the following consideration: the support system was designed
to prevent an outward rotation hinged on the travertine blocks. In this case, the arch is
positioned correctly, as distant as possible from the rotation center - the blocks - in order to
provide the maximum restoring effect without having to develop an excessive compressive
force, which, in turn, could crush the concrete core of the arch. With the arch preventing the
rotation, the load carried by the travertine blocks is predominantly vertical and therefore
sliding of the blocks can be safely ignored. The notion that a vaulted structure could collapse
through outward rotation is consistent with the collapse mechanism of an arched structure
built with stone blocks (*opus quadratum*), a type of failure certainly known to structural
designers in Trajanic times - fig. 16. Therefore the design intention can be interpreted as the
creation of a modular structural form, derived from intersecting arched configurations and to
be constructed in *opus caementicium*, but conceived to behave - and thus fail - like a masonry
block structure. The weakness of the design reflects the ignorance of material behavior. Thus
the Great Hall resulted from an engineering practice that had yet to acquire the correct
mechanical understanding of how an arched structure in *opus caementicium* fails. Perhaps, its
near structural failure provided the stimulus and the necessary visible evidence for developing
this knowledge.
In engineering practice, successful design is based on the analysis of failure. In the introduction to a series of case studies of failure in the design process from antiquity to the present time, Petroski stresses that “…practicing engineers … learn much more from failures that from successes.” Making the case for studying historical cases of failure, he notes: ”For all its use of sophisticated mathematics and computational models, design today involves the human mind in fundamentally the same way it did for the first builders.” Thus, historical case studies “… may generally be considered among the most objective and natural sources of data on the design process that are available.” The study of the structural deficiencies of the Great Hall must have been of the greatest importance to the Roman engineer, who needed to develop new paradigms for designing large-scale concrete cross vaults. This study is no less relevant today, in our attempt to understand how technical knowledge was created in antiquity. To extract the data, however, we need to properly understand and then accurately model the mechanics of opus caementicium near and beyond the strength limits, so that we can follow the propagation of fractures up to structural collapse. These objectives, which will require extensive experimental studies and nonlinear Finite Element modeling, are part of our ongoing investigation of the Great Hall.

In concluding the present study, we want to stress an important point, clearly shown by our analytical models but seldom mentioned in discussing Roman building engineering. Because of the inherent weakness in tension of Roman concrete, the design of vaulted systems of large dimensions in opus caementicium inevitably leads to structures working in near-limit conditions, possibly outside of the safety margin stipulated in modern building codes. It is an extraordinary achievement in the history of structural engineering that, working within the tight constraints imposed by the material, Roman designers were able to conceive an effective structural configuration that allow them to build some of the largest and long-lasting masonry vaults in history. The Great Hall and the structural challenges it poses are likely the place where this extraordinary achievement began.

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