Concrete vaulting in Imperial Rome: A structural analysis of the Great Hall of Trajan’s Markets

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Abstract

The Great Hall of the Trajan’s Markets in Rome is the oldest surviving example of a cross vaulted structure built entirely in Roman pozzolanic concrete (opus caementicium). The Finite Element method is used to investigate the structural behavior of the Great Hall under static gravitational loads and with the assumption of Roman concrete behaving as a linearly elastic material. The results of the analysis are in excellent agreement with the observable fracture patterns in the vault and in the lateral arches. The study shows that, contrary to the commonly held view in the literature, the lateral arches do not perform any contrasting action due to incorrect positioning. However, the structural skeleton of the Great Hall, characterized by the innovative use of lateral arches, shear walls, and supporting travertine blocks, can be regarded as the earliest prototype of the structural solution adopted for the design of gigantic concrete vaults.

1. Introduction and objectives

The Great Hall occupies a preeminent position within the Trajan’s Markets, the imperial building complex on the Quirinal hill overlooking the Forum of Trajan in Rome – Figure 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 meters long and 8.8 meters wide, built entirely in Roman pozzolanic concrete (opus caementicium). The vault itself, consisting of a series of six cross vaults resting on travertine blocks and connected to the adjacent structures by lateral arches, can be regarded as the precursor of the gigantic vaults in opus caementicium used in Roman imperial baths and basilicas from the second to the fourth century AD.

The Markets of Trajan have been studied extensively by archaeologists and art historians since being brought to light by the 1926-1934 excavations and restorations, with particular attention often reserved for the Great Hall. Because of its series of cross-vaults and corbelled travertine support piers, the Great Hall was soon regarded as an innovative architectural form, made possible by the concrete revolution in Roman Imperial architecture. Beginning with the earliest study (Giovannoni [2]) the lateral arches were identified as structural contrasting elements, necessary to oppose the horizontal thrusts generated by the large concrete vault – Figure 2. Their perceived functional role made them true – and perhaps earliest – precursors of the flying buttresses of Gothic cathedrals.
In recent years, a series of in-depth archaeological studies of the Great Hall have shed additional light upon aspects ranging from the construction to the definition of internal components and their qualitative function as a structural whole (Lancaster [3].) Still, perhaps the most striking features of the hall – the physical structures of the vault and its support system – have not been subjected to engineering structural analysis. Thus, the functional identification of the lateral arches as flying buttresses has been reaffirmed over the years by several authors based solely on qualitative reasoning, see, for example, the recent work by Addis [4].

As part of an interdisciplinary research on the engineering design of concrete Roman vaults conducted in collaboration with the Museums of the Imperial Fora in Rome and the University “La Sapienza”, Rome, we are investigating the structural behavior of the Great Hall through Finite Element (FE) stress analysis. In the present paper, we limit the discussion to the response of the structure under static gravitational loads. The primary objectives are: (1) develop an understanding of the mechanics of deformation of the vault and the supporting system; (2) identify areas subjected to elevated tensile an compressive stresses; (3) determine the functional role of the lateral arches; and (4) attempt an evaluation of the structural design of the Great Hall.

2. Methods

All FE models are based on a three-dimensional solid model derived from a survey of the monument and representing the structural skeleton of the Great Hall isolated from the other buildings in the Trajan’s Markets. The model – shown in Figure 3 – is comprised of the concrete vault (red), the supporting travertine blocks (white), the lateral arches (blue), and the concrete transversal shear walls and piers (green). This solid model is used to create a series of local and global 3-D meshes consisting of quadratic tetrahedral elements.

The opus caementicum used in the Great Hall is a conglomerate consisting of a coarse aggregate (primarily tuff but also brick pieces) embedded in a pozzolanic mortar.

Following the experimental data for a Roman pozzolanic conglomerate of similar composition provided by Samuelli Ferretti [5] for the Basilica of Maxentius, the opus caementicum is modeled as a linear elastic isotropic material with modulus of elasticity equal to 3 GPa, mass density 1540 kg/m³, and Poisson ratio 0.2. The compressive strength of this material is 4 MPa and the tensile strength is conservatively set at 0.1 MPa. All the FE analyses assume infinitesimal strains.

3 Results

Two sets of boundary conditions are used to simulate the mechanics of the supporting travertine blocks under gravitational loads: either fully constrained (no relative motion between the blocks) or with rollers allowing the upper block to slide in the horizontal plane. A more accurate modeling of the contact conditions, involving both sliding and rotations, requires a nonlinear FE approach and is beyond the scope of the present paper.
3.1 Deformation

The primary deformation mechanism – shown in Figure 4 – consists of a downward sag (bending) at the crown accompanied by an outward displacement at the springing of the vault. There is no outward displacement at the attachment of the lateral arches. Following the motion of the vault, the arch is deflected downward while the attachment section rotates. Sliding of the blocks markedly increases the magnitude of the deformations without significantly altering the deformation pattern. Analyses of the structure with the lateral arches removed indicate that the deformations are not affected by the presence of the arches. The removal of the shear walls, however, is shown to substantially increase the magnitude of the deformations, especially in correspondence of the supporting blocks.

3.2 Stress distribution

The bending deformation at the crown induces tensile stresses at the intrados of the vault, Figure 5, forming a band that extends along the entire length of the vault, Figure 6. These stresses exceed the tensile strength of the material. Nuclei of tensile stresses, also exceeding tensile strength, are also present at the attachments of the lateral arches, due to bending of the arches, Figure 5. As for the displacements, the removal of the lateral arches does not affect the stress distribution at the intrados or extrados of the vault, while the presence of the concrete shear walls below the travertine blocks plays a critical role in controlling the magnitude of the tensile stresses in the vault. All compressive stresses are well within the compressive strength of the opus caementicum.

4. Discussion

The numerical results are validated by comparing the computed stress distributions to the pattern of fractures observable in the structural skeleton. We then address the functional role of the arches and finally present a tentative evaluation of the structural design of the Great Hall.

4.1 Validation of the FE results

A longitudinal fracture, visible in pictures taken during the original restoration and subsequently repaired with brick insertions and injections of modern concrete, traverses longitudinally the entire intrados of the main vault, in excellent agreement with the distribution.
of tensile stresses predicted by the model – Figure 7. Similar repaired fractures are found in the later vaults. Results also suggest that the lateral arches may have been weakened by tensile stresses acting at the attachments. In fact, only few of the original arches have survived, often with major repairs. The predicted tensile stresses match the observable fracture patterns at the attachments of several arches. Arguably, the collapse of the other arches may be taken as a further proof of the accuracy of the predicted stresses.

4.2 Functional evaluation of the lateral arches

The lateral arches do not function as contrasting arches under static gravitational loads. The numerical results, supported by the physical evidence, indicate that the vault does not produce a horizontal thrust at the level of the arches. As shown earlier, the arches are subjected to bending and shear but not compression. Their presence does not contribute in any appreciable way to controlling the deformation, and therefore the stress state, of the vault. Perhaps, considering that this is the earliest free-standing cross vault in opus caementicium which has survived, we should regard the lateral arches as an initial, and partially failed, attempt by the Roman engineers to create a stabilizing element for a new type of structural form.

4.3 Structural design of the Great Hall

The design of monumental cross vaults made possible by the opus caementicium set forth new challenges for the Roman structural engineer that can be summarized as follows. The structural form and the intrinsic weakness of concrete to tension produce fracturing at the intrados of the crown accompanied by large thrusts at the springing of the vault with the potential for catastrophic collapse. These challenges were resolved in part by developing a design based on lateral shear walls, contrasting arches, and supporting blocks and in part by reducing the weight of the vault as much as possible. As shown in Figure 3, these elements are all present in the structural skeleton of the Great Hall, albeit at different state of refinement. Thus, while the shear walls are effective in reducing the tensile stresses, the contrasting arches are not properly positioned to counteract the lateral thrust, which, acting at the level of the travertine blocks, may cause these to slide and rotate. The presence of ancient dovetail clamps and the damage on the blocks suggests that these motions may have taken place, worsening the fractured state of the vault. In conclusion, the structural analysis of the Great Hall shows that its designer was moving in the correct direction, formulating a new structural scheme that, once perfected, would have made possible the construction of gigantic vaults such as those at the Baths of Caracalla and Diocletian and at the Basilica of Maxentius.

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