Analysis of a Roman masonry flat-slab in Hadrian’s Villa, Tivoli

D. Abruzzese, G.E. Cinque & G. Lo Gatto
University of Rome “Tor Vergata”, Italy

ABSTRACT: The study concerns the research of the architectural and structural shape of an ancient building in villa Adriana in Tivoli, Italy. Particularly, the building has been investigated in order to answer questions about the status of its roof. The problem has been studied under geometrical assumptions based on data collected by the survey, but even under historical and architectural considerations reported in the literature about ancient roman building. The interesting result is that a large room of this Villa could be covered with a flat slab made with roman concrete and no reinforcement.

1 INTRODUCTION

1.1 Ancient Roman masonry

At the beginning of the II century A.D., when Hadrian was Emperor, Roman building techniques were improving.

The building technique for vertical walls was well known and widespread. Large areas could be covered by the use of the Roman concrete, because of its adaptability to the shape of the brick, used as casting mould.

Concrete vaults were the most common techniques for Romans to cover large rooms. Builders used simple and double curvature vaults: barrel vaults, groin vaults, dome vaults, and others with more complicated shapes. It is important to notice that the biggest concrete vault, covering the Pantheon was built under Emperor Hadrian. The diameter of the Pantheon’s dome is 42 m.

1.2 Three Exedras building in Hadrian’s Villa

Hadrian built his Villa during his own reign, between 118 and 138 A.D. near Tivoli, not very far from Rome (Fig. 1). The Villa is spread over approximately 120 hectares, but was probably larger. In ancient literature, Hadrian has always been considered an architect, and probably he himself was the architect designer of many buildings in the Villa.

In the Villa there was not only the emperor’s residence, but even many other buildings, such as theatres, baths, peristyles and habitations for his large court, for the army and for servants. The Villa probably became the place where he and his architects tried to create new shapes and make new experiments, just like the dome of the Small Baths, whose shape reminds us of those of the later baroque period.

The Three Exedras building is located in the Villa, in one of the areas first built.

The “building” case of this study lies near the so called Poecile, and in the literature is named “the east wing” of the Three Exedras building (Fig. 2). The building is unique because of its flat slab roof of very simple geometry. The building is symmetrical and its large central room is a rectangular area of 9 m x 16 m. The room was probably covered by a concrete flat slab, whose fragments now lie on the floor.

1.3 Methodology of study

The study of the roofing of the Three Exedras building was executed in three main steps:

1. The first step is the collection of geometrical and construction data of the building as we can see at present, and of the fragments of the masonry
The collection of information has also been supported by a bibliographical research and by collecting paintings and pictures of old buildings belonging to the same period, or even much later (Renaissance) but referring to similar shapes.

2. In the second step, several hypothesis were formulated about the roofing and its structural behavior, and the hypothesis were then checked by structural analysis.

3. Finally, a virtual architectural model of the building was made according to the hypothesis checked analytically and with archaeological concepts. The model represents the building in its original state, in Hadrian’s time.

2.2 Three Exedras building-description

The building’s geometry is very simple and it is composed by a rectangular part and a semicircular one, whose diameter is 23.30 m (Fig. 3). This area is one of the Three Exedras of the building with that name, which is strictly connected with the east wing. The building is symmetrical and inside it has 7 rooms, two lateral rooms have an apse, while the large, rectangular central room, 16.2 m × 9 m wide, has another small room attachment at a slightly higher elevation (about 0.30 m). This part is like a balcony looking at the near Garden Stadium. The function of the building is still unknown. The vertical walls have a regular thickness of 0.60 m (equivalent to two “Roman feet”), composed by three parts. In the external parts we have bricks arranged in the way of opus reticulatum used as casting mould into which the concrete was poured, thus becoming the core of the wall. The walls’ height is 7–8 m, so they themselves bear witnesses of the skill of ancient Roman bricklayers.

The general condition of the masonry is still good, though many vandals during the building’s life ruined it and stole marble and even deteriorated bricks. At any rate, the masonry’s conditions have been improved by several interventions of restoration, the first of which was made in the early XX century.

The building’s floor lies on suspensurae, which is an ancient roman heating system, composed by a square frame of small pillars made of bricks (0.30 m × 0.30 m). The information comes from a surveying program using geo-radar techniques. During the study, it was possible to use this investigative system directly because of a hole in the pavement of the room, originally hidden by soil, plants and stone fragments. The hole showed a praefurnia system, where the Romans ligthed their fires to heat the building.

2.3 Fragments of the ancient flat-slab

Several fragments of an ancient concrete flat-slab lie on the building’s floor.

The fragments, which are composed by several layers, had been surveyed and measured (Fig. 4).
Figure 5. Plan of the flat slab's fragment on the floor.

Figure 6. Layers in the flat slab's fragments.

Some of them still lie in the same position since the flat slab fell down (Fig. 5). It is evident because when they fell down they broke the floor which is supported by suspensurae.

The fragments' dimensions are very different: the largest has an area of about 2 m², and the smallest are about 0.20 m long. The lower and the upper surfaces are parallel and inside 7 different layers can be identified on variable thickness of 0.40-0.50 m (Fig. 6).

The composition of the flat slab from the upper to the lower layer is showed in Table I.

Table 1. Composition of the flat slab.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Composition</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>a.</td>
<td>Mosaic</td>
<td>0.03 m</td>
</tr>
<tr>
<td>b.</td>
<td>Lime mortar, fine grained</td>
<td>0.045 m</td>
</tr>
<tr>
<td>c.</td>
<td>Lime mortar, bigger grained</td>
<td>0.11 m</td>
</tr>
<tr>
<td>d.</td>
<td>Cocciopesto, variable</td>
<td></td>
</tr>
<tr>
<td>e.</td>
<td>Opus spicatum</td>
<td></td>
</tr>
<tr>
<td>f.</td>
<td>Lime mortar, fine grained</td>
<td>0.045 m</td>
</tr>
<tr>
<td>g.</td>
<td>Lime mortar, bigger grained</td>
<td>0.11 m</td>
</tr>
</tbody>
</table>

Even the ground floor is composed by two layers just like layer b and c, and of the same thickness, but above layer b there was an other one: the mortar to connect the flooring tiles.

The technique for the concrete flat-slab is described by many ancient writers, among whom is Vitruvius. However, no one wrote about opus spicatum inside a floor; usually used as a floor material.

The fragments lie on the floor of the whole building, but mostly in the lateral larger rooms. The total of the area covered by the fragments is 87 m², while the whole building's floor is 446 m² wide. The fragments' area represent 3% of the area of room E, and as much as 31% for room C. Totally they are 19%, but probably they covered the whole building's area at Emperor Hadrian's time, because the Villa had been plundered since it was abandoned by the Emperors and the court, until the early 1900. Besides, the fragments have never been measured and surveyed. So we don't know how many fragments there were before the great restorations in the early 1900. We just know that the fragments had been shifted during several restorations, except for those that were too large and heavy to be transported.

3 STRUCTURAL ANALYSIS

3.1 Structural model

Structural analysis of the covering needed to consider several models that could fulfill the requirements.

In particular, attention was paid on three problems:

1. Flat slab material characteristics: it was important to notice that there were different concrete layers and each one behaves in a different way if stressed by tensile stress or compressive stress.
2. Choice of restraints at the edge of the flat slab.
3. Structural behaviour according to the way it was poured.
3.1.1 Material characteristics hypothesis

Nowadays, when we design a reinforced concrete structure, we do not consider that concrete could resist tensile stresses.

The most important problem of the hypothesis of this work is that the flat-slab necessarily should be stressed by high tensile stress.

In this kind of material, the critical stress is the cracking strength stress value. The real material composing the fragments is very good, so in this study we considered that the material of the model could resist to tensile stresses up to the value of 2.0 MPa.

It is noted that the material's behaviour is different if it is stressed by compressive or tensile stress: the concrete's modulus of elasticity decreases when passing from compressive to tensile stress; so neutral axis of a section under simple bending moment goes from the middle part of the section to the upper part.

Besides, the flat slab was composed of 7 layers, different in thickness and material, and each layer had its own modulus of elasticity. It would have been very difficult to make a model that considers both the characteristics (several layers and different behaviour).

The problem was first simplified to a concrete flat-slab composed of only one homogeneous and isotropic material. But other two examples were analyzed: 1. homogeneous material but anisotropic when stressed by compressive or tensile stress (Fig. 7); 2. isotropic material but the section is composed by 4 layers of the same thickness but each one with his own modulus of elasticity. The last example was just a theoretical case study, but quite close to reality if we knew all the characteristics of the material.

The mechanical characteristics of the model’s material are those assumed by the architect Salza Prina Ricotti. The architect was the first one that tried to demonstrate that the building’s covering was a concrete flat slab, and in this study the same material characteristics were used, in order to compare different results.

Table 2. Geometric and elastic characteristic of the concrete flat slab.

<table>
<thead>
<tr>
<th>g</th>
<th>Density</th>
<th>2.000</th>
<th>kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>Modulus of elasticity</td>
<td>20.000</td>
<td>MPa</td>
</tr>
<tr>
<td>σₘₐₓ</td>
<td>Tensile maximum stress</td>
<td>2.0</td>
<td>MPa</td>
</tr>
<tr>
<td>h</td>
<td>Height of the flat slab</td>
<td>0.50</td>
<td>m</td>
</tr>
</tbody>
</table>

3.1.2 Hypothesis on the flat slab’s restraints

The flat slab is simply supported by the vertical walls, so the restraint in the model is that one of simple support. In fact it is impossible to think that the concrete of the flat slab and the walls could be merged and have structural continuity. Probably the flat slab was built when the construction of the vertical walls was finished, and it was simply posed on the walls. But the support’s dimension depend on the model of the original building. We do not know the original architecture and the building process, that is why we had several different hypothesis, and some of the models we used are from Salza Prina Ricotti’s work.

Since other details on the covering are not known, it is impossible to suppose the presence of vertical walls on the edge of the flat slab. These walls could improve the condition of tensile stresses in the concrete flat slab.

3.1.3 Hypothesis on the structural behaviour

The flat slab could have been built in two different ways: it could have been poured at one time in one big formwork or in more than one in many formworks. In this second case the formwork was 2.2 m long and the width of the same room dimension. This hypothesis is supported by the observation that a fragment lying in the central room 2.2 m long, has three sides orthogonal to each other.

A different structural behaviour would occur if the flat slab was poured all at one time or in several layers: in the first case it could be considered a plate, but in the second one it could behave as a series of beams.

Generally, considerations about masonry, assume inability to take tensile stress: this is the case when arching occurs within the thickness of the flat slab. But this could not be possible since the pressure arch had a low curvature and the thin and high walls could not resist to the high horizontal thrust.

In the next step analytical calculations were made for the various hypothesis on the restraints and the material characteristics (Table 2).

4 ANALYTICAL OUTPUTS

4.1 General characteristics

Different considerations have been made for the following models. The density of the chosen material
is $\gamma = 2000 \, \text{kg/m}^3$, and the modulus of elasticity $E = 20,000 \, \text{MPa}$ is constant in the whole thickness of the flat slab, however in some cases we considered a different modulus in order to make a careful study of the various examples.

The thickness of the flat slab has been fixed in 0.50 m, but we didn't consider the different layers, except for the case study with 4 layers of the same thickness but different values of the modulus of elasticity.

The calculation was developed for the covering of the large central room, but even for the lateral rooms. About the observation on restraints we considered always simple supports concentrated on one line in correspondence with the resultant of the distribution of the reactions at the supports.

These characteristics change if the width of the support changes or if the two parts – the support and the flat slab, or two flat slabs – have different stiffness.

Besides the crack value of concrete for tensile stress has been fixed at $\sigma = 2.0 \, \text{MPa}$. This value is very high but we have to consider that the concrete of the fragments is still very good. The results of some test on sample of similar old roman concrete in the area of Hadrian's Villa gave values between 0.9 and 1.5 MPa, with indirect “brasilian” test (G.P. Giani, M.Candiago Zich, 1991), while compressive test gave value of the resistance between 10 and 30 MPa. We are still elaborating some new tensile test, but the high quality of the material leads to consider a higher value of tensile resistance, at least one tenth of compressive value. The crack value and the yielding stress are the same, so the material in the model doesn’t have any plastic reserve. In order to study the ultimate resistance of a rectangular section some simulations have been done changing the isotropic properties of the material or the tensile crack stress maximum value. These studies showed that the ultimate moment of the section increases if modulus of elasticity ratio increases (compressive modulus/ tensile modulus) (Fig. 8).

This observation allowed a simulation of the stratification of different materials by creating a model composed by 4 layers of the same thickness. They had different modulus of elasticity but if the stiffer layer is on the upper part and the other are less and less stiff, the section could have a higher ultimate moment. Thus, the use of material could be more efficient (Fig. 9).

The compressive crushing stress of the model's material is similar to the usual value of common masonry. Failure occurs because of the tensile crack value is achieved, while the material still has a compressive stress reserve.

4.2 Beam model
The beam model considered for the building's covering is similar to that one assumed by the architect Salza Prina Ricotti. The scheme has 4 main cases and 3 derived from the last one (Figs 10–11).
Tensile stresses were studied, where, in the moment diagram the values of the moment were maximum. The study was developed not only for the central room, but also for the lateral rooms. In some cases the tensile stress is too high in the lateral flat slabs, even if they are smaller than the central one.

The main schemes used were composed by simply supported beams but in some cases there were positive bending effects, because of observations on the point of the simple support and on other forces (Fig. 12).

In all the main 4 cases the crack tensile stress of 2.0 MPa was achieved. Other times, only little bit below the crack value was achieved, but this is highly unlikely in very real situations.

In the last 3 cases, derived from the 4th of the principal ones, the flat slab of the central rooms is stretched out, goes over the central wall and is the support for the central flat slab. The moment diagram reveals that the tensile stresses are too high in the lateral room flat slab, even if the dimension of the cantilever changes.

In the last of the 3 cases, derived from the principal one, the tensile stress value is acceptable. In this case the central room was covered by a wooden truss roof and it was supported by the two lateral concrete flat slab.

This solution is not in contrast with the information we have from the paintings or pictures that represent the building’s front elevation. Particularly the drawings from Penna belonging to the 19th century before the great restoration of the early 1900, suggest that one of the three cases above could occur. In the drawing, a small cornice could underline the presence of the concrete flat slab. The cantilever part could span 1 m.

Besides, it is evident that some of the fragments in situ are in the same positions in which they were when the flat slab fell down: and their position is in keeping with this hypothesis. So the model has been accepted; but probably some of the previous models could provide interesting results if the material model was improved.

4.3 Plate model

This model would be useful if the flat slab was poured at one time in a large formwork large just like each room in the building. But in this case only the plate of the central room has been developed in this study because worst condition would occur in this room's covering.

The software used for the calculation of this model was Lusas Rel.13, a computer code for Finite Element Analysis. The main model for the roof is a plate of 9 m x 16 m, with 0.5 m of thickness, simply supported by the vertical walls on the lower edge (Fig. 13).

The software has been used to create a mesh that was useful to evaluate stress and displacement values in a more accurate way.

The first plate model that has been analyzed was made of an homogeneous and isotropic material whose characteristics are:

\[ E \text{ (modulus of elasticity)} = 20000 \text{ MPa} \]
\[ \nu \text{ (Poisson's modulus)} = 0.3 \]
\[ \gamma \text{ (density)} = 200 \text{ MPa} \]

In the central part of this kind of plate, loaded with its own weight, there are the higher stresses in a symmetrical way:

\[ \sigma_x = 0.993 \text{ MPa} \quad \sigma_y = 1.93 \text{ MPa} \]

In this model there is no difference between the material’s behavior if it is stressed by tensile or compressive stress, so an other case study was developed: the material’s characteristics are the same, but it is divided into two parts. In the upper part, above the neutral axis line the modulus of elasticity is \( E = 5000 \text{ MPa} \) while in the lower part \( E = 20.000 \text{ MPa} \). The neutral axis line has been calculated for a rectangular section with pure bending moment.

In this simulation the maximum tensile stress is \( \sigma_y = 1.31 \text{ MPa} \). This value could be accepted but we should make a comparison between it and the beam model composed by a similar material.
Besides, as we don't know the real ratio between the modulus of elasticity, this example is just a simulation. At last another case study has been developed: if it was composed by different layers and the stiffer was in the upper part the tensile stresses would decrease.

5 GRAPHICAL HYPOTHESIS OF THE ORIGINAL STATE

The only believable analytical model, after the static analysis results, is the one in which the central room was covered by a wooden truss, but supported by the concrete flat slab stretching out of the lateral rooms.

So a graphical model was made using this hypothesis. The model shows the original state of the building at Emperor Hadrian's time (Fig. 14).

Not only static analysis results had been used in order to build the model, but even the information from ancient drawings and plants, bear witness to the building's conditions in past times. The drawings show the building before restorations, and give more information about it.

Besides the Regional Authority for Archeological Heritage ("Soprintendenza") for the Lazio Region, which is the tutor of the Villa, provided much information and suggestions about the virtual reconstruction model. Also some ancient roman example of similar architecture contributed to create the model.

It was impossible to ignore the presence of the other buildings surrounding the Three Exedras' East Wing in order to create the model, because all of them are strictly connected to each other from the architectural point of view.

In the model the height of the building and of the elements on it is strictly connected with the survey of the actual state; only when it was impossible to get information out of the survey some proportions have been chosen similar to building of the same age or of Renaissance times.

The three-dimensional model shown in Figure 13 presents the most likely shape of the building, according with the hypothesis assumed and the results of the structural investigation.

Figure 14. Final virtual graphic model of the building in the original state.

6 CONCLUSIONS

The study of ancient buildings can be developed in order to identify static problems not only to restore and reinforce them, but even to analyze various hypotheses and build a model of the original state.

The function of many of the buildings in Hadrian's Villa are still ignored, because the buildings in the Villa are not typical, such as basilicas or forum or residences.

We can imagine that the Villa was a particular place where the Emperor and his architects invented new forms and shapes, because of the 'architectonical freedom' that the Villa allowed. These new architectural experiments also concerned structural and building novelties.

Sometimes buildings of the Roman age were not so solid and resistant and for the weaker ones, that probably ruined, there is no historical record. We have knowledge only of the stronger buildings that had characteristics of high resistance. It is noteworthy that the buildings and monuments, which remained in good conditions until today, were well designed in the framework of the architectural and building traditions, following the construction rules experienced over several centuries.

Most probably, new experimental buildings had low safety coefficient (the Romans couldn't evaluate the suitable safety coefficient until they experienced several new buildings). We can remember that several gothic cathedrals fell down during the middle ages.

The knowledge of the hypothetical original state of an ancient roman building contributes to give information to archaeologists, but it is also a sign of the technological progress that Romans had achieved in that period.

The simulation of the flat slab of the east wing of the Three Exedras building is living proof that, even with an extremely low safety coefficient, this kind of roof structure probably existed. This general hypothesis is also supported by some archaeologists, such as Salza Prina Ricotti, mostly from architectonical considerations.

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