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The Trajan Markets and their Great Hall – The conservation problems and the structural intervention for the improvement of the seismic safety

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ABSTRACT: This paper focuses both on the analyses carried out and on the interventions designed and built for the structural behaviour improvement of the main building among those that compose the Traiano Markets in Rome. The Traiano Markets were subjected to all the last four big earthquakes of Rome, with the last one accursed in 1703 and with a return period of around three-four centuries, but the present geometrical and structural configuration of the Markets is different and weaker respect the original one and also weaker respect their configuration in the 1703. Numerical analyses by Finite Element Method (FEM) have been applied, emphasising the seismic vulnerability of the structure. In particular, the performed numerical analyses allowed the identification of the most vulnerable parts of the supporting structures as well as the assessment of an adequate retrofitting intervention criterion, based on the use of reversible techniques.

1 INTRODUCTION

The Great Hall Vault of the Trajan Markets is one of the largest and very impressive among the remaining original roman vaults. It is made by roman pozzolanic concrete with a very thick shape which allows a nearly monolithic behaviour, just reduced by the possible negative effects of many cracks. But the weaker structural elements, in case of seismic actions, are the supporting structures. These last are today not sufficient and/or not sufficiently laterally counteracted to resist to the horizontal actions associated to seismic effect on the Great Vault mass.

On site investigations have been devoted to the identification of the geometry of the main structural parts and elements as well as of the mechanical features of the constituting materials of the Great Hall Vault and of its supporting structures. These surveys have suggested to carry out some numerical analyses which have shown the weak behaviour of the supporting structures. Thus it was designed, numerically verified and finally applied an adequate retrofitting intervention, based on the use of reversible techniques.

2 THE MONUMENT AND ITS STRUCTURE

The term Great Hall is applied to a building laid out on four levels starting from Via Biberatica. The principal level is therefore the second floor, which is on the same level as Via Quattro Novembre. The Great Hall, intended for public functions, forms an independent block clearly defined and circumscribed.

The main level consists of a very large rectangular room 36 meters long and 8.50 meters wide. The pavement, made by bricks and travertine slabs, dates from the 1930s.

On the ground floor facing east, a number of rooms of different depths open onto this large room. By contrast the rooms facing westward are regular in form, they open into each other, and have windows. On the first floor are two passages running along the longer sides of the building and articulated by low masonry arches set between the pillars of the Hall and the longitudinal walls of the room. The rooms are small: on the east side they are again irregular and windowless; on the west side they are regular and have windows. Finally, on the west side alone, there is a

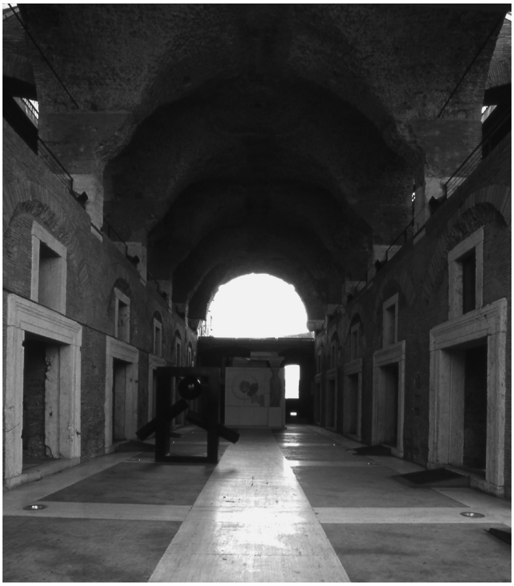

Figure 1. The Great Hall in 2007 after restoration works.

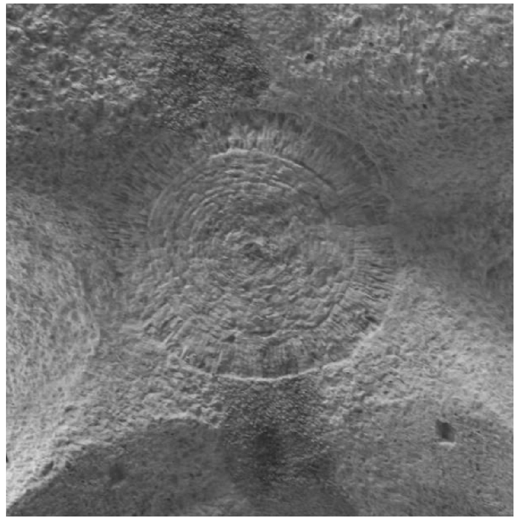

Figure 2. The oculus after restoration works.

further level consisting of a series of vaulted rooms largely restored and ranged above the ones below. All of the rooms of the Great Hall are vaulted and have portals in travertine.

The roof of the Great Hall is the result of the join between of the six bays of barrel vaulting on the smaller side with the principal side running from north to south. This consists of six groin vaults resting on pillars, faced in the lower part with travertine and in the upper part with a brick curtain wall. The pillars had large corbels which have been preserved only in part on the shorter side towards Via Biberatica and the side facing Via Quattro Novembre.

The weight of the roof, ca. 1250 tons, is transferred to the walls of the rooms below by the pillars and just a little onto the second-floor rooms through the low arches lining the two side passages.

On the basis of the archaeological evidence as well as Renaissance views, the vaulting alternated with projecting arches made of brick resting on the heads of the corbels (Bianchini, Vitti 2003). The arches and the corbels in travertine were removed with the installation of the convent of St Catherine of Siena, when an attic story was added which divided the Great Hall in half (Ungaro 2003).

The covering of the Great Hall represents a forerunner of the great vaults that were later employed on an immense scale in subsequent centuries to cover even larger spaces in baths and basilicas.

The restoration of the vault also made it possible to verify precisely the alterations begun in 1574 with the construction of the convent of St. Catherine. This involved cutting through the projections of the travertine corbels, the points of attachment to the walls for an attic in the central room on the level of the first-floor passages, and their covering by means of small groined vaults. The most interesting discovery is the blocking of the large central oculus set in the summit of the vault and documented by photographs taken during the alterations in the 1930s. The oculus does not date back to the period of Roman construction but is prior to 1546, when it appears in an image of the Great Hall in the altarpiece of the "Stoning of St. Stephen" by Giulio Romano. During the construction of the cloister, the oculus was adapted as an intake for air and light for the new spaces laid out on the first floor, with a band of brickwork running round its perimeter. Finally in 1926–1934 it was closed with bricks arranged in a radial pattern. After the removal of the modern cement facing in 2006, it was left visible (Ungaro & Vitti 2007, Vitti 2007).

3 THE VALORIZATION AND MUSEALIZATION OF THE GREAT HALL

The extensive complex of Roman buildings built of brick, known by the conventional name of Trajan's Market, has miraculously survived to our own times from the heart of the ancient city, close to the great squares of the Imperial Forums, and still in the centre of the modern city.

This entailed very difficult problems of adaptation, which had to be solved while respecting the integrity and image of the monument, first of all with the closure of the principal and rear elevations of the Great Hall.

Figure 3. Closure in acrylic panels of the arch of the Great Hall facing Via Biberatica.

This had to be done while respecting the ancient structures, without recreating an arbitrary design for the facade, providing proper protection from pollutants, and securing structural safety and the greatest possible transparency. The scheme adopted consists of a modular system of large acrylic glass sheets linked by uprights in the same material fixed to steel plates, so reducing the impact on the monument to a minimum while providing the essential protection and favouring its use.

The fact that the complex is laid out on six levels entailed the provision of vertical connections. They were provided in the upper part of the complex by an oleo-dynamic elevator, which links the three levels of the Great Hall and the Central Block with the Giardino delle Milizie (Ungaro 2007).

Investigations to ascertain the structural compatibility between the museum and the structures of the complex emphasized the need for extensive conservative intervention and structural consolidation.

4 THE STRUCTURAL BEHAVIOUR BEFORE THE RETROFITTING

4.1 *The transversal behaviour and the crack patterns*

The Great Hall structures, that surround and contain the Great room, only apparently form a thick body with a squared plan; on the contrary they are two bodies, separated by the Great room itself (Fig. 4). These two buildings develop their plan parallel to the Great Vault axis, in the NE-SO direction. Thus, both of them are weaker in the transversal NO-SE direction.

Among them, the northern one appears more sound as it is less high and transversally thicker. Vice versa, the Southern one is thinner and higher as it starts from the level of Via Biberatica (Fig. 4).

The weaker conditions of the Southern building is shown by the crack pattern also, with a clear tendency to the detachment of the Southern façade on Biberatica Street. Moreover, it is necessary to take into account that these two buildings have to support the big mass of the Great Hall vault, under static and seismic actions too. From this point of view, it is important to notice the weakening of the transversal wall, in the Southern building, caused by the doors placed near the Southern façade, at the same level of the Great Hall pavement. The seismic action of the past, are the causes of the cracks on the arches over the doors said before and of the cracks on the transversal walls, in the lower level, just under those doors and near the southern façade; cracks that show a clear weak condition under the Great Vault thrust (in NO-SE direction) with also a clear tendency to a detachment of the Southern façade on Biberatica Street (Fig. 5).

Figure 4. The Great room, in the centre, which divides the Northern building, on the left, from the Southern one, on the right; note the lower level of via Biberatica respect the Hall.

It must be taken into account that, before the retrofitting, the transversal seismic acceleration of the Great Vault mass is alternatively supported only by the Southern building and only by the Northern one (changing the sign of the acceleration itself); as it is easy the arise of hinges in the key and in the springing of the Great Vault (Fig. 5). Moreover, this behaviour may be accentuated by the different transversal stiffness of the two building, as this difference can easily cause opposition of phase in the transversal oscillations of the two buildings.

4.2 *The longitudinal behaviour, parallel to the Hall axis*

The seismic action longitudinal component founds a very weak structural configuration in the vault supports at the "matronei" level. All the supporting pillars and the counteracting lateral arches, have their main stiffness planes in the transversal direction while the weaker ones are in the longitudinal direction (Fig. 6).

It is important to notice that the present masonry structural configuration is due to the restoration works carried out in the twenties and thirties of the last century, when they were demolished all the not original roman masonries added along the centuries and especially in the XVI century.

Thus, and especially at the "matronei" level (Fig. 6), the structure is weaker than in the period from the XVII up to the XIX century and also weaker than the original configuration, as some roman structural elements (some secondary vaults) are disappeared, along the past centuries.

4.3 *The numerical analyses*

The analytical study of the vault and its surrounding structural elements was carried out by means of a numerical 3D model developed for the static and dynamic structural behaviour evaluation, using the Algor program produced by Algor Inc.

The 3D Finite Element mesh is refined in such a way to describe with an adequate accuracy all the constructive details, using 3D "brick" finite elements.

Figure 5. The Southern building weak behaviour and the collapse mechanism in case of transversal seismic action.

In Table 1 they are reported the material mechanical characteristic (specific weight, Young modulus and Poisson coefficient) used for the different parts of the structure.

About the seismic spectral acceleration, the present Italian Code states a ground acceleration of around a = 0,192 g at the building foot, which means an amplified acceleration of around a = 0,260 g at the Great Vault level.

In Figures 7 and 8 are reported the results of the seismic static equivalent analysis in the transversal direction, while in Figures 9 and 10 are reported the static equivalent analysis in the longitudinal direction.

In Figure 7, all along the intrados of the vault key there are tensile stresses that reach the 210 kPa and justify the deep and large cracks visible before the last restoration.

It is important also to notice in Figure 8 the strong compression stresses in the foot of the short pillars supporting the Vault: the minimum principal stresses reach the 1822 kPa.

However the worst situation arise with the seismic action in the longitudinal direction.

The static equivalent analysis reported in Figure 9 shows the risk of overturning for the pillars engaged along their weaker section axis: the vertical stresses reach 1142 kPa in the compressed side; while reach 311 kPa in the side on tensile stress. The little arches that laterally counteract the vault (Fig. 10), are unable to resist to the longitudinal seismic action, as in this

Table 1. Material mechanical characteristics.

Material	Weight kN/m^3	Young mod. kPa	Poisson mod.
Caementicium	15	2.000.000	0.15″
Travertino	24	20.000.000	0.10″
Cocciopesto Mortar	18	200.000	0.20″

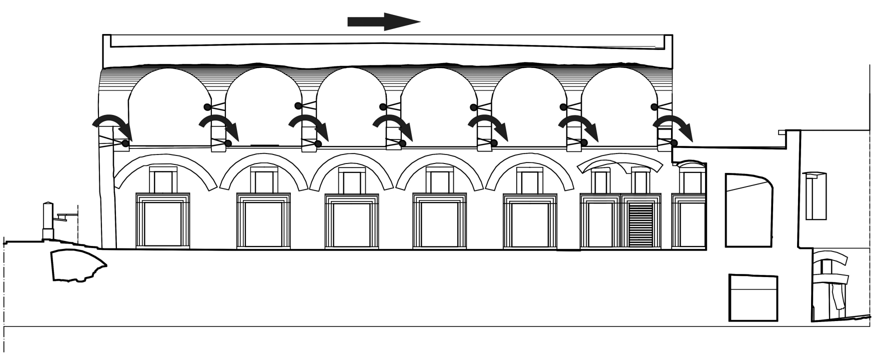

Figure 6. The possible overturning collapse mechanism of the pillars supporting the Great Vault, at the "matronei" level, in case of longitudinal seismic action.

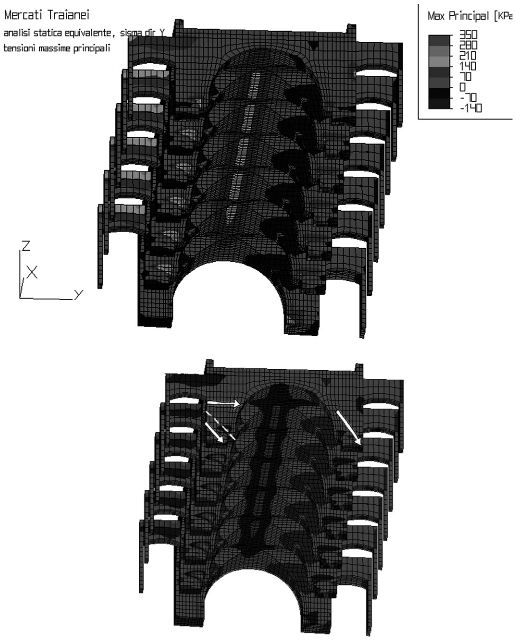

Figure 7. The max. principal stresses in the Vault and in the pillars with the transversal static equivalent seismic action.

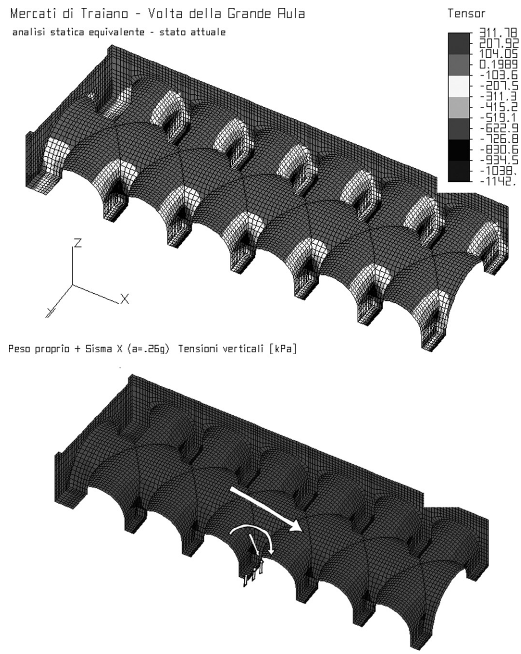

Figure 9. The vertical stresses in the pillars with the longitudinal static equivalent seismic action.

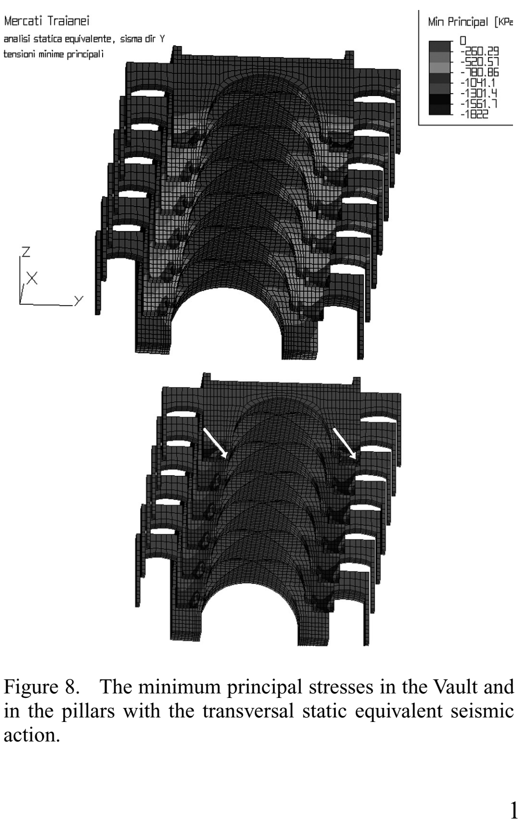

Figure 8. The minimum principal stresses in the Vault and in the pillars with the transversal static equivalent seismic action.

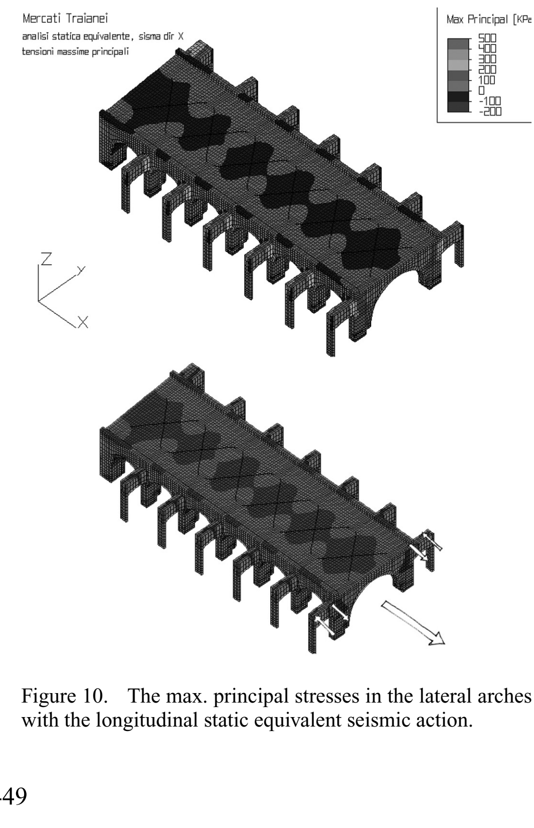

Figure 10. The max. principal stresses in the lateral arches with the longitudinal static equivalent seismic action.

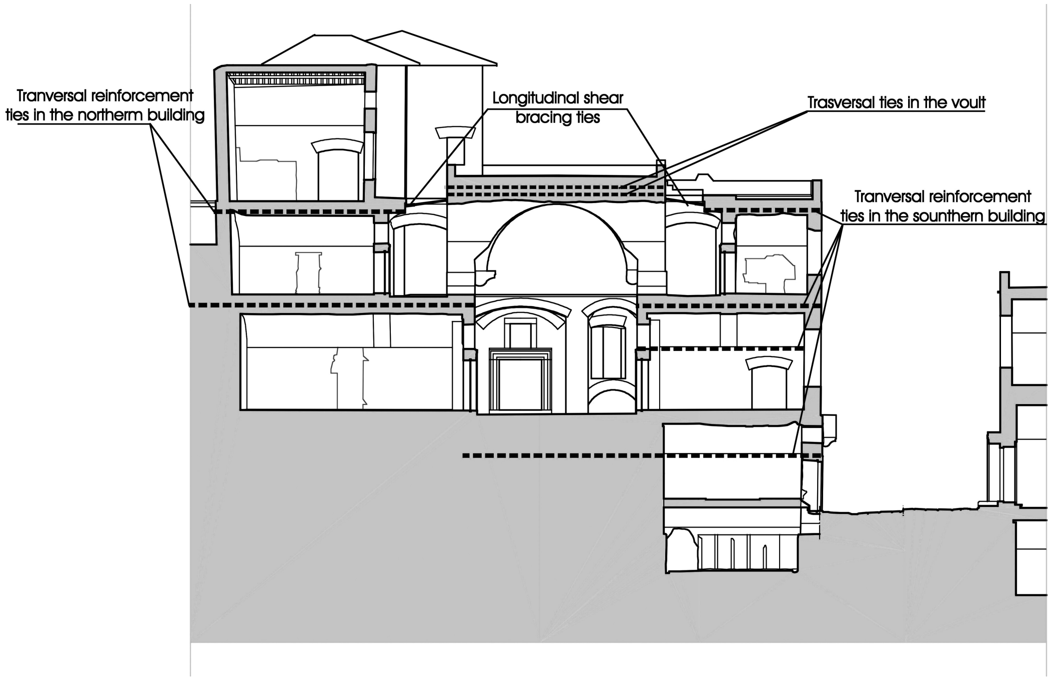

Figure 11. The distributed transversal reinforcements at the different levels.

case they are bent horizontally, out of the proper arch working plane, reaching tensile stresses up to 350 kPa.

5 THE REINFORCEMENT INTERVENTION AND RETROFITTING

5.1 *The intervention philosophy*

Evaluating the opportunity to "improve" the seismic behaviour of an historical building, it is important to study its global structural behaviour, but it is also necessary to check if each structural element may compromise, with localized failures, the structure as a whole.

In the case of the Trajan Markets Great Hall, there is a clear "global" weakness in the transversal structural behaviour, due to the weaker configuration of the Southern building, in case of seismic actions in NO-SE direction; but, at the same time, there is a "localized" weakness of the pillars supporting the Great Vault in case of seismic actions in NE-SO direction.

The failure of only one of these pillars may cause the collapse of all the Great Vault.

In the case of historical buildings, the seismic behaviour improvement has to be obtained with the minimal alteration of the original structure.

Thus it is better to apply a "diffused" and "reversible" intervention instead of a more strong and concentrated one, which last is necessarily more invasive and, thus, also less reversible.

A "diffused" intervention has to be extended as more as possible to all the structure, in such a way to better connect the different structural elements, to guarantee their collaboration and, thus, to use more efficiently their original strength.

On the contrary, too localised interventions may cause the alteration of the original global behaviour, more higher stress concentrations and, thus, also possible local damages.

In the case of the Great Hall, for the transversal (NO-SE) seismic component, it was necessary a "diffused" reinforcement of the transversal shear walls, mainly in the Southern building.

At the same time, for the longitudinal component (NE-SO) of the seismic actions it was decided to not to try the reinforcement of each pillar supporting the Great Vault; on the contrary it was designed a shear braced horizontal stiffening to connect, on both the longer sides, the Great Vault mass to the Northern and to the Southern buildings.

5.2 *The transversal reinforcement*

The intervention is a system of horizontal ties, distributed on each transversal wall of the two buildings supporting the Great Vault, in such a way to improve their shear strength in the NO-SE direction.

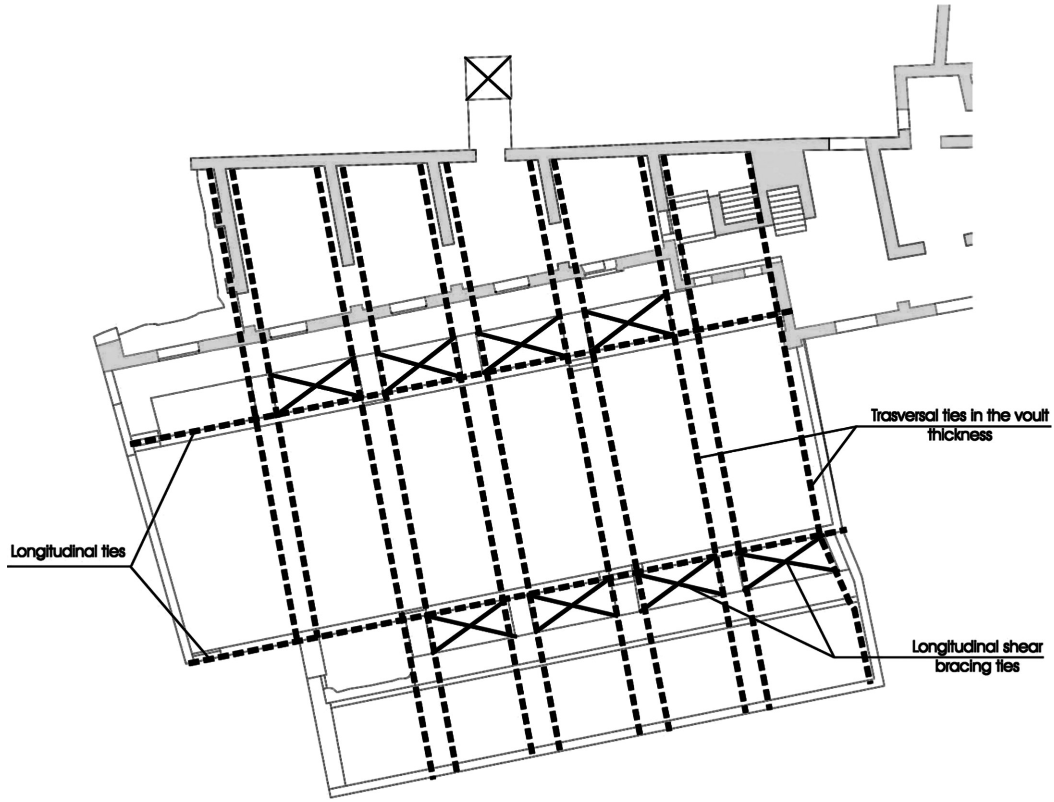

Figure 12. The plan view of the distributed transversal reinforcements and the diagonally counterbraced shear reinforcements.

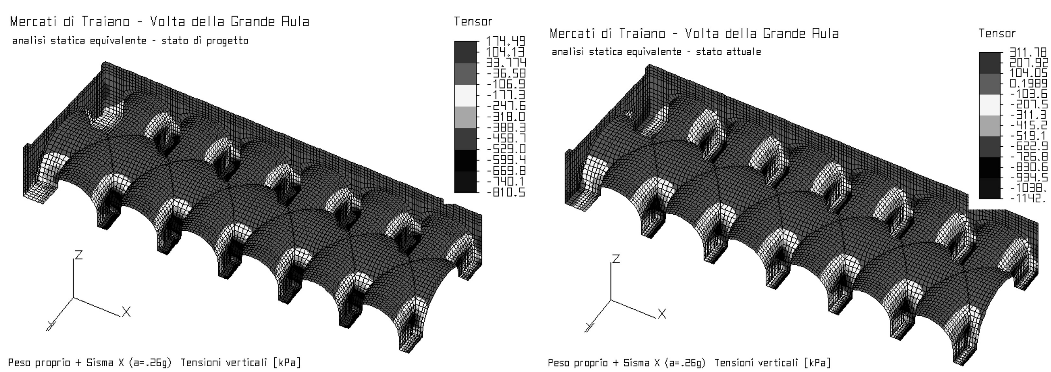

Figure 13. The vertical stresses in the pillars after the intervention, on the left, and without the intervention on the right.

More in detail, in the weaker Southern building these ties are distributed not only on each shear wall but also on each level, as shown in Figure 11.

Moreover, as shown in Figure 12, for each shear wall it is placed a couple of bars nearby each side of the wall itself, instead a single one, in such a way to be less invasive, avoiding to drill horizontally those walls for all their length.

To guarantee the collaboration of both the buildings in counteracting the Great Vault mass thrust, during a seismic action, they are placed horizontal connections over the two series of lateral arches among the two

Figure 14. View of the southern lateral longer side of the Great Vault with the diagonally counterbraced shear reinforcements placed in the free spaces between the Vault itself and the Southern building, nearly the ending of the work.

buildings and the Vault itself. Then they are placed also some ties, across the Vault, inside its thickness, also to counteract the effect of possible not in phase transversal oscillations of the two buildings.

Thus it is placed a system of horizontal distributed ties also in the Northern building, but only at the III and IV level, in such a way to involve its transversal shear walls all along their length.

The distribution and the number of these ties placed in the two buildings and in the Vault, allow to reduce their diameter down to 22 mm.

5.3 *The longitudinal diagonal braced shear reinforcement*

The intervention is a system of nearly horizontal stainless steel diagonally counterbraced shear reinforcement, placed in the free spaces among the great vault and the lateral buildings, just over the "matronei" level (Figs 11 and 12).

This shear reinforcement is designed in such a way to transfer to the two lateral buildings, parallel to the Hall axis, the main part (around the 65%) of the longitudinal seismic action involving the Great Vault mass, reducing the overturning moment on the pillars supporting the Vault itself.

Four free spaces on each side are occupied by the diagonal counterbraced reinforcements and each diagonal is made up by two tie bars with 22 mm of diameter (Fig. 14). Thus during a longitudinal seismic action 16 diagonal braced tie bars work together at the same time.

5.4 *The numerical analyses*

The numerical model, which simulate the reinforcements through stiffening boundary elements along the two longer side of the Great Vault, show a clear improvement in the Vault structural behaviour.

Particularly in Figure 13 is reported the stress reduction in the pillars supporting the Vault, in case of longitudinal seismic action: compared to the case without reinforcements, the static equivalent analysis shows as the vertical stresses are reduced from 1142 kPa to 810 kPa, on the compressed side, while the tensile stresses are reduced from 311 kPa to 174 kPa.

6 CONCLUSIONS

The Trajan Markets Great Hall shows a high sensibility to seismic actions.

This fact is due to the weakness of its supports: the weak structural behaviour of the Southern building, in case of transversal actions, and the weak behaviour of the pillars at the "matronei" level, in case of longitudinal actions.

While in the first case there is an indirect risk of collapse for the Vault, related to the possible partial failure of the Southern building, in the second case, with the longitudinal component of the seismic action, there is an immediate risk of collapse af the Vault as a whole, related to the easily overturning of the pillars.

The intervention designed and already applied, with its "distribution" calls the collaboration of all the supporting structures, reducing the efforts of the single structural elements.

In this way, avoiding stresses concentrations, they are not present alterations of the original structural conception.

Moreover, the reversibility of this intervention typology is a warranty for the possibility to use the future probable improvements in the retrofitting techniques.

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