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Finite element analysis of an old building façade and reinforcement

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SUMMARY

The Podestà Palace, a historical masonry construction, is dated from the XII century and is situated in Foligno, central Italy. This building has a high heritage and artistic value associated to it, mainly due to existing paintings in both the internal and external parts of the façade. Its current deteriorated state, coupled with the high seismic hazard of the region, stresses the pronounced seismic risk associated to this building. However, possible conservation and strengthening measures to be potentially applied should not affect the architectural and historical value of the Palace, i.e. its authenticity.

In order to assess the seismic vulnerability of the building, a numerical model was developed. The reduced global dimensions of the building made possible the development of a simple model comprising only the consideration of the façade. The boundary conditions, due to effects of the walls perpendicular to the façade, pavements and vaults as well as the effect of the neighbouring building and later additions were duly considered. A previous and detailed structural survey of the building, together with existing architectural drawings, made possible the development and construction of a finite element mesh of the Palace's façade. The numerical model was subjected to the self-weight of the structure and to lateral loads that took into account earthquake loads according to the Italian code.

The results demonstrate that during a standard earthquake, partial or total collapse of the building should be expected. The careful analysis of the critical areas that lead the structure to collapse made possible to determine an appropriate methodology for structural strengthening, having always in mind the minimum intervention - maximum efficiency approach.

Through a careful analysis of the weakened areas that caused the building collapse, it became possible to determine the best methodology for the structural strengthening, being chosen the reinforcement with carbon fibers, that allowed a localized reinforcement. In the last part of the study, the model was updated with the inclusion of the FRP strengthening and subjected to the same loads applied on the second part of the study. The results show that, due to the use of FRP composites, the collapse was avoided through the reduction of the displacements normal to the façade surface.

As a conclusion, the carbon fibres located in strategic areas, increased the building façade resistance by reducing the perpendicular displacements. The strategic location of the carbon fibre becomes imperceptible, and this way, less intrusive to the patrimonial value of the construction.

INTRODUCTION

The Podestà Palace, a historical masonry building, is dated from the XII century and is situated in Foligno, central Italy. This building has a high heritage and artistic value associated to it, mainly due to existing paintings in both internal and external parts of the façade. Its current deteriorated state, coupled with the high seismic hazard of the region, stressed the pronounced seismic vulnerability associated to this building. However, possible conservation and strengthening measures to be potentially applied should be planned and designed not to affect the architectural and historical value of the Palace, i.e. its authenticity.

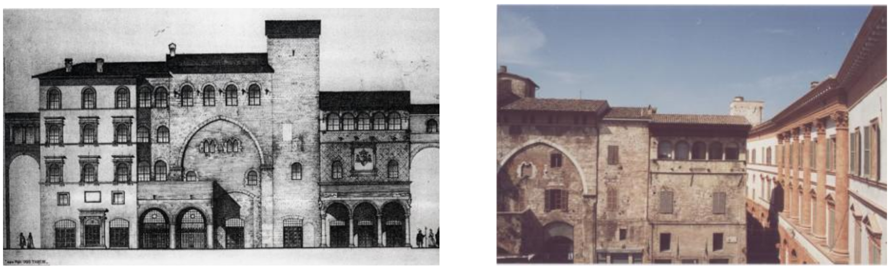
In order to assess the seismic vulnerability of the building, a numerical model had to be developed. The numerical model was subjected to the self-weight of the structure and to lateral loads that took into account earthquake loads according to the Italian code. The numeric analysis results allow to understand the building structural behaviour and to determine the most stressed elements. The careful analysis of the critical areas that lead the structure to collapse made it possible to determine an appropriate methodology for structural strengthening, always having in mind the minimum intervention - maximum efficiency approach.

PODESTÀ PALACE

Historical survey

The Podestà palace is a XII century building situated at the Repubblica Square, main Square of Foligno city, in the Umbria region, central Italy. This palace is part of a building compound that formerly, due to the local power, was physically united in the past, as can be observed in figure 1. Nowadays, due to its history, heritage and artistic value, this structure is considered a symbol of Foligno's history, together with the neighbouring palaces (Trinci Palace, Priori Palace and the city Duomo).

Apart from its historical and heritage value, the Podestà palace has on its façades a special characteristic that distinguishes the building from the other palaces in the old city. In fact, the paintings on the interior and exterior walls make this building unique.



(a) (b)

Figure 1 - Podestà palace: (a) U. Tarchi Drawing; (b) General view.

Structural survey

Being this palace an old palace, the structure suffered several changes along the time, mainly because of different uses, but also for aesthetic reasons or even due to restoration works. Through a detailed visual inspection, very important information was obtained for the execution of a correct structural analysis.

Knowing that the most important collapse mechanisms happen in the building's main façade and, in this particular case, the main façade is the most valuable part of the building, it was decided to study the main façade only, taking in to account the effects of perpendicular walls, pavements and vaults of the structure as well as the effects of the other structures attached to it and the later strengthening interventions. More comprehensive information can be found at Barros et al. (2005), or Carocci et al. (2006). In relation to the collapse mechanisms, in this particular case, the out of plane collapse mechanism is not a problem because it is prevented by the existing reinforcement with existent metallic elements in the building main façade. The detailed structural survey conjugated with the architectural documentation makes possible to recreate the building's main façade structural model.

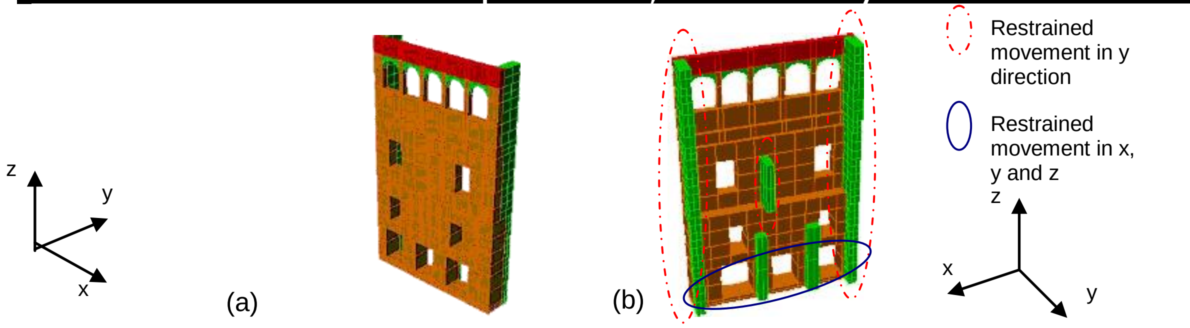


Figure 2- Palace façade geometric model: (a) Front; (b) Back.

NUMERICAL ANALYSIS

Modeling strategy

The software used to perform the finite elements analysis allows to represent the structural element characteristics as well as the existent material properties of the structure. Comprehensive information and specific knowledge about the finite elements software ANSYS can be found at Madenci et al. (2006) or Moaveni (2003).

Given the difficulty of recreating masonry elements in this type of software, the mesh made for analysis, of 25cm x 25cm, allows us to identify the displacements and alterations in structure with a high precision degree. Non-linear material properties where considered, namely tensile and compressive strength. The finite elements analysis made in this study, consists of a non-linear material analysis, in which the loads in the structure are applied in an incremental way.

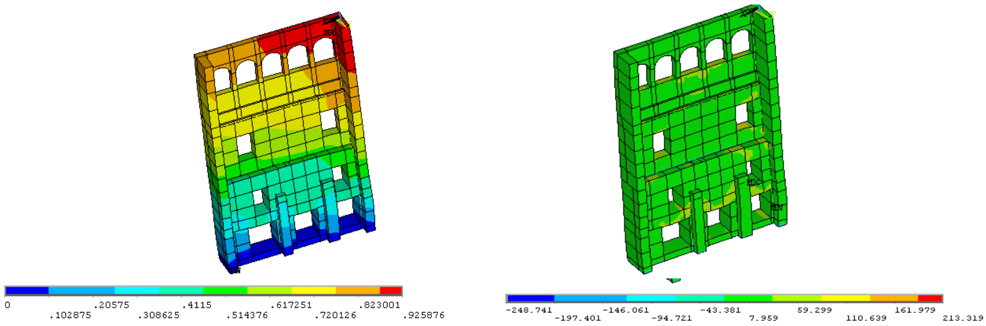
Vaults

Before analyzing the behavior of the façade, the building's individual models of crossed and pavilion vaults, were prepared in order to assess their contribution to the structure. The vault's models were created with the Rhinoceros software through solid elements and closed surfaces. After the preparation of the 3d Cad vaults models and, then, using those geometric models in the analysis program (ANSYS), information about the displacements, reaction forces at supports, maximum and minimum stresses and their locations were obtained (Barros et al., 2007). With the data obtained in the analysis of the vaults, it was possible to take the results to the main façade structural model, recreating the vaults effect on the façade.

Main façade

The numeric analysis was divided in two different parts. The first one was made considering only the structure self-weight, while, in the second analysis it was considered the self-weight and also a seismic force. In both analyses the forces were applied in an incremental way. The seismic analysis was made only in the direction of the façade and not in the normal direction, because the façade is tired with iron tie rods that prevent perpendicular movements to the façade, and as this reinforcement worked well during the earthquake in the Umbria region in 1997, the analysis of the effect of the seismic force in the direction of the façade was thought to be more important.

The first analysis intends to recreate the current stress state of the façade. For this purpose, all the existent elements that influence the behavior of the structure were represented. These elements are the continuous foundation, perpendicular walls and neighboring buildings attached to façade, floors, timber roof, iron tie rods and vaults. Recreating the existent situation and subjecting the façade model to test through the finite elements software maximum displacements of about 9 mm (figure 3a), maximum compressive stresses of 0,241 MPa and maximum tensile stresses of 0,213 MPa (figure 3b) were obtained (Barros et al., 2007). These results represent specific zones where pick values are reached, being related to the cross vaults support areas (maximum tensile stresses) and foundations (maximum compressive stresses). Considering the loads applied, these results can be considered normal.

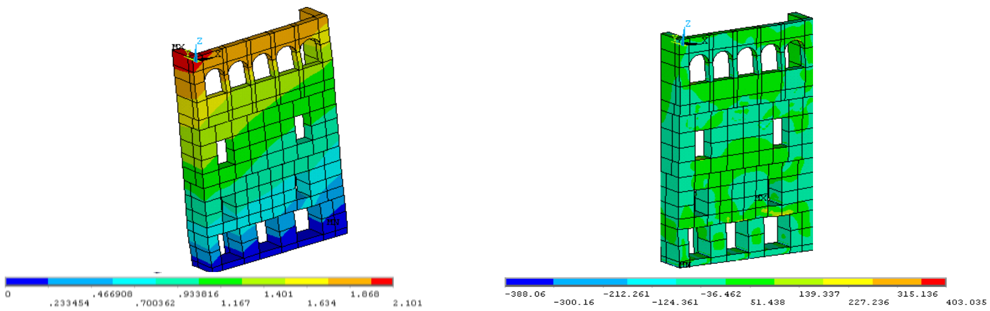


(a) (b)

Figure 3- First analysis results: (a) total displacements (cm), (b) first principal stress (KPa).

In the second analysis, the model is subjected to equivalent static forces by means of lateral acceleration applied through increments, corresponding to a peak ground acceleration of 0,35g (Ordinanza 3474-3431) in x-x direction. The values reached are maximum displacements of 21mm (see figure 4a), maximum compressive stresses of 0,388 MPa and maximum tensile stresses of 0,403 MPa (see figure 4b), which demonstrate the actual risk of the structure during a possible earthquake occurrence. Under the effect of lateral forces, the in-plane façade displacements are quite high, creating tensile and compressive zones, which lead to the structure local collapse.

The maximum values obtained in the second analysis are localized values. It seems that they are relative to the crossed vaults supporting areas (maximum tensile stresses) and foundation (maximum compressive stresses). However, these values are quite high values, which may cause significant damages in the structure, because the structure drift is about 0,2%, which is between 0,1% and 0,4%, considered by Magenes and Calvi as a dangerous range.



(a) (b)

Figure 4 - Seismic analysis results at the last converged increment: (a) total displacements (cm), (b) first principal stress (KPa)

Having in mind that the obtained values are relative to detailed areas of the façade and that the software determines the numerical collapse when there is a rupture in these areas, it may be necessary the design of structural reinforcements that allow the structure to surpass the obtained rupture and, in this way, avoid the total collapse of the Podestà palace façade.

STUDY OF A STRUCTURAL REINFORCEMENT SOLUTION

Due to the need of a low intrusive methodology, the option was the reinforcement through FRP, reaching a precise, effective and low intrusive solution. The option of using FRP in the reinforcement, allows a more located reinforcement. This way, with the intention of reducing the displacements detected in the second analysis, it was decided to apply carbon fibers, in the vaults support areas, inside the façade. Were also applied, carbon fibers in two areas in the exterior of the façade, in the top of the façade and in the pavilion vaults support areas.

In the last analysis of the study, the reinforced model is subject to the same test made in the second analysis, and this way, the numeric collapse of the building was avoided through the increase of the resistance capacity to the perpendicular displacements in the façade plan and, in the same way, through the building capacity increasing to resist to higher compression and traction forces.

This way, after the building reinforcement, the maximum displacements results increased for 33,4 mm (figure 5). The same happened with the maximum traction tensions of 0,60 MPa and the maximum compression tensions of 5,64 MPa. These last ones, in spite of the high value, it can be considered normal, being relative to the compression maximum values obtained in the carbon fiber registered by the software, and not in the structure in itself, as can be observed in the figure 6.

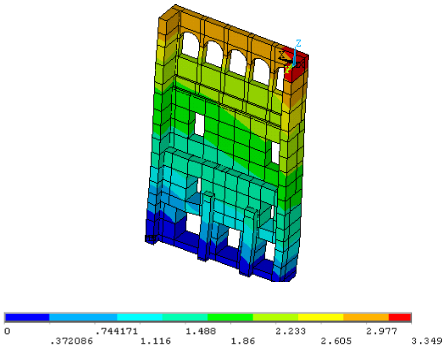


Figure 5 - Seismic analysis results with exterior FRP reinforcement: total displacements (cm).

This way it was confirmed that a structural reinforcement through a precise and low intrusive intervention, as the case of the use of carbon fibers, can allow to reinforce weakened local areas and, this way, to avoid the Podestà palace collapse, safeguarding his patrimonial and architectural value.

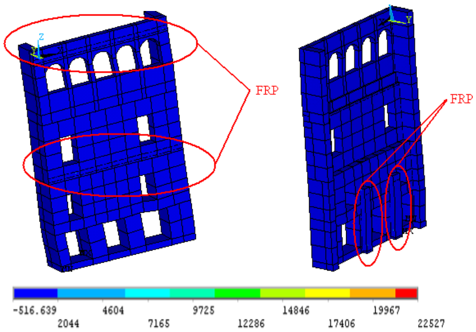


Figure 6 - Seismic analysis results with exterior FRP reinforcement: first principal stress (kPa)

CONCLUSIONS

The Umbria region is a high seismic hazard zone, according to the Italian regulations. This means that, in this specific peninsula the structures are subjected to considerable earthquake forces. Therefore, historical structures as the one described here, which are vulnerable against earthquakes, are especially under risk.

In this project two different analyses were carried out in order to identify the behavior of Podestà palace in Foligno. In the first analysis, which considers the effect of self-weight of the structure, the results present no critical displacements or stresses. The problems are local and can be solved by local interventions. However under the lateral forces, which are applied to the structure considering the seismic properties of the zone, the displacement and stresses are beyond safety limits, most probably leading to the collapse of the structure.

From the information coming from the analysis of the structure, it is evident the need to make further and more complex analysis and to propose an intervention methodology in order to decrease the vulnerability of the structure without altering the historic and aesthetic values of this architectural heritage.

The solution of carbon fiber application is a viable option, because with the application of these reinforcement elements, we can reach satisfactory results through low intrusive and structural efficient interventions.

This way, in the third analysis made with the finite elements method, a FRP reinforcement was applied in the façade specific areas, considering the obtained results in the second analysis, in other words, in the weakened façade areas.

With this reinforcement and due to the good operation function of the carbon fiber applied in the building weakened areas, it was possible to avoid the numeric collapse obtained in the second analysis and, this way, verify an increase of the building resistant capacity when subject to a seismic phenomenon.

In conclusion, reinforce with carbon fibers when applied strategically, can increase the building façade safety, namely controlling the façade perpendicular displacements. The use of carbon fibers in the reinforcement becomes imperceptible, and this way, low intrusive. This is a fundamental aspect considering the Podestà palace patrimonial value.

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