Suggestions on Improving the Seismic Performance of Portuguese Old ‘Pombalino’ Buildings

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Abstract. There was a destructive earthquake in Lisbon, 1755. After that earthquake people built ‘Pombalino’ masonry building in Lisbon downtown. As time goes by, these buildings need to be reinforced and refitted because of the degeneration of the elements, the requirements for seismic performance and the new functions these buildings should be adapted to. This paper aims to provide some suggestions on how to reinforce the ‘Pombalino’ building and improve the seismic performance. These three suggestions are discussed and concluded by the theoretical analysis of three kinds of reinforcement measures, which include strengthening the connections with FRP elements, pasting carbon fiber sheets to improve the shear strength of masonry, setting laminated rubber pad isolation system to improve the seismic performance and the advantages and feasibility of these suggestions. Considering the advantages of the FRP materials, which are discussed in the following paper, the FRP connecting elements, as well as carbon fiber sheets can be a good choice to replace the aging connecting elements. To improve the seismic performance of this building, laminated rubber pad isolation system can be installed to absorb the energy caused by earthquake and reinforce the degenerated piles footing.

1. Introduction
Portuguese Pombalino masonry buildings were built mainly in Lisbon downtown after the 1755’s Lisbon Earthquake. It was composed of an interior three-dimensional braced timber structure named gaiola enclosed in masonry walls above the first floor aiming at providing resistance to horizontal forces. The Gaiola is constituted by a set of plane trusses, called frontal walls, connected at the corners by vertical bars that belong to orthogonal frontal walls. Each frontal wall is constituted by a set of triangles, a geometry similar to the steel trusses of nowadays [1]. The inclusion of the timber braced structure was proved to be an efficient anti-seismic provision, since the gaiola presence increases the building global stiffness to seismic actions and the out-of-plane displacements of the front façade are reduced due to the presence of this structure [2]. However, the dissipation of seismic energy coming from the ground is questionable for this kind of timber frame inside the masonry is built only above the first floor and because of questionable connections and forced components of the timber to masonry.

In addition, the location of these architectures, which is the center of Lisbon, determined that they were endowed with some new functions and demands. As a result, the conversion of these buildings brought new problems. For instance, some pipes set in these buildings destroyed the timber frame so the capacity of the timber structure reduced apparently. Another example is that people demolished the exterior masonry walls of many houses to change the ground floor into shops and banks. Therefore, the building vulnerability to shear base collapse mechanism increases. All these problems are supposed to be considered when reforming theses building to get better earthquake resistant behavior.
Most rehabilitation works are performed to adapt old Pombalino buildings to new functions or to repair damage due to age. But the seismic reinforcement is seldom because the high cost and the absence of realization to the seismic problems. Based on the theoretical analysis of three kinds of reinforcement measures, in the following paper, the author will analyze how to reinforce the aging connection elements as well as how to improve the global stiffness and seismic performance ultimately.

2. Replacing the Aging Connection Elements with FRP Components.

For the low strength connection between the timber elements and the masonry, the FRP components can be used in the strengthening of timber reinforced masonry load-bearing wall.

FRP is fiber reinforced polymer/plastic. When used in building structure, the commonly used fiber materials are carbon fiber and glass fiber. The matrix materials are epoxy resin, vinyl ester resin and unsaturated polyester resin. The fiber is the first arranged in a certain direction or woven into the form of board and cloth, and then bonded with the matrix material to form FRP products. There are many benefits of FRP materials. Firstly, FRP is light weight. The density of FRP is about 14 to 21Kn/m³, which is about 1/6 to 1/4 of that of steel. When applied to many building structures, it can greatly reduce the self-weight of the structure. Taking Steve Jobs Theater as an example, the weight of the whole carbon fiber roof is only 80t, which can be constructed by integral hoisting method. According to the roof diameter of 47m, the average weight per square meter is 46kg, which is only equivalent to about 6mm thick steel plate. Such an amazing weight reduction effect makes it possible for the roof to bear on the surrounding structural glass, creating an amazing space effect. Secondly, FRP has high strength. There are defects in the crystal structure of natural materials. The finer the materials are and the fewer the defects are, the higher strength the crystal structure will get. The strength of carbon fiber and glass fiber can reach 10 to 20 times of steel. Considering the strength difference between fiber and matrix of FRP materials and steel, the strength/weight ratio of FRP material is usually 4 times of steel. The ultimate span of FRP long-span structure is 2 to 3 times larger than that of traditional structure. Some researchers have demonstrated that the use of CFRP cables to build 10000 meters span of the Gibraltarian bridge can be seen from this.

Thirdly, FRP is easy to be molded and assembled. FRP production process includes pultrusion, winding, hand paste, spray molding and other ways. It cannot only produce FRP products with regular shape on a large scale, but also produce almost arbitrary shape plates for building nonlinear building modeling. FRP has a variety of connections modes including bolt connection, and its material portability makes it easier to disassemble and assemble.

Compared with steel connection elements, FRP elements are far superior. Most of the connection elements between the timber and the masonry are ties as shown in figure 1, with small size and complex structure. These factors determine that it will be difficult for these ties to mould and assembled. But various production processes of FRP solve this problem. Besides, the small size means that it will not cost too much, so most owners can afford this kind of ties. Figure 2 shows how FRP ties connect timber elements of the floor to masonry.

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Figure 1. FRP ties connecting timber elements of the floor to masonry walls.
And for the low strength connection between the timber elements, FRP can also be applied to the reinforcement. Figure 3 shows typical connections between timber members. The vertical and horizontal members are cut (grooved) at their mid-sections for them to be connected. In Figure 3b illustrates how two diagonal elements are attached together. These are also grooved at half their thickness to be attached to each other. Considering Lisbon is a coastal city and the location of ‘Pombalino’ building is close to the sea, the steel elements would be corroded by moisture and salt in air. But the excellent corrosion resistance of FRP overcome this problem. Also, because of the high strength and the advantages of molding and assembling, FRP nails become a better choice for the reinforcement members.

3. Applying Carbon Fiber Sheet to Improving the Shear Force of Masonry and Reinforcing the Members of Pombalino Buildings.

Masonry low shear strength may be critical to shear failure of the building due to the formation of a global shear collapse mechanism. One of the methods to improve shear strength is using steel mesh to confine masonry structural elements of façades.
However, there are problems of this method. Firstly, the fixtures of the steel mesh are a kind of damage to the masonry. It may also damage or even cut the timber section like the pipe, both of which should be avoided they interfere within the timber structure. Another limitation is that this method might last for a long time and make a lot of noise. Considering the function of these buildings, the large-scale construction should be chosen carefully.

Another possible solution is carbon fiber sheet. This kind of cloth is pasted on the structure so the construction is fast and convenient and it will not damage the masonry or the timber elements. The excellent mechanical properties also can be satisfied with the reinforcement of the ‘Pombalino’ building.

Carbon fiber sheet (CFRP) reinforcement is a new type of strengthening method, that is, the epoxy resin bonded carbon fiber cloth is pasted on the structural members to be strengthened along a certain direction, so as to combine and bear the force together to improve the strength, stiffness, crack resistance and elongation of the strengthened structural members. The contribution of CFRP strengthening to the overall behaviour in terms of lateral strength and stiffness, effects of different application techniques and connection details were investigated experimentally and analytically [4]. Carbon fiber sheet is suitable for reinforcement and repair of various structural types and parts, such as beams, slabs, columns, roof trusses, piers, bridges, cylinders, shells and other structures. It is suitable for the reinforcement of concrete structure, masonry structure and wood structure in port engineering, water conservancy and hydropower engineering, especially for complex structure reinforcement such as curved surface and node. Compared with the traditional reinforcement method, the application of carbon fiber sheet has the following advantages.
Firstly, the self-weight of carbon fiber sheet is only 200-300g/m², and the design thickness is 0.111-0.167mm. In addition, the self-weight of epoxy resin series bonding materials is also very light. Therefore, the application of carbon fiber sheet reinforcement basically does not increase the self-weight and section size of the building structure. After the reinforcement, the impact on the building load and celebrate is very small, and the appearance of the original structure of the building will not be affected [4].

Secondly, carbon fiber material has excellent physical and mechanical properties, such as good softness, can be flexibly used for bending, sealing hoop and shear reinforcement. It has high tensile strength, which is 4 to 8 times of ordinary steel, so it is suitable for reinforcement of reinforced masonry structure. At the same time, it has the properties of high and low temperature resistance, abrasion resistance, chemical resistance, which means that the corrosion resistance and durability are greatly improved.

Thirdly, the construction of strengthening with carbon fiber sheet is simple and easy to be operated. There is no need for large machinery and equipment, no wet operation, no fire work, no fixed facilities on site. It does not need large construction organization and transition materials, which shortens the construction period.

In conclusion, carbon fiber sheet can play a good role in strengthening the building with the least impact. For shear reinforcement and seismic reinforcement, the fiber direction should be perpendicular to the axial direction of the component.

4. Retrofitting the Foundation with base Isolation System

This foundation system of Pombalino buildings is based on a tridimensional grid of wood bars on top of short length (around 1.5 m) and small diameter (around 15 cm) wood piles, which are embedded on a large embankment made with the debris of the buildings destroyed by the 1755 earthquake and compacted by the piles. The embankment receives the loads from the structure through the wood grid and piles and distributes them by a larger area of the underlying alluvium, reducing the stresses at this level. However, the strength and seismic performance of wood piles and the grid of wood bars is questionable for the degeneration caused by the erosion of ground water, which is illustrated in Figure 6. For the Pombalino buildings have their fundamental frequencies of vibration within the band of frequencies where the energy of earthquake ground motions is maximum, the seismic ground vibrations will be amplified by the structure. The structure also produces accelerations within the structure that increase from its bottom to its top. Hence, these amplified structural motions can cause severe distress in the structural elements and large relative motions between different parts of the structure. This may lead to permanent damage to different parts of the structure or may even lead to catastrophic collapse.

For this problem, one possible solution is retrofitting the foundation with base isolation system. This system aims to shift the fundamental frequency of the structure away from dominant frequencies of the fixed-base superstructure. Besides, it provides an additional means of energy dissipation to reduce the transmitted acceleration into the superstructure. These benefits of base isolation are pioneered by Vasant Matsagar and R. S. Jangid [5].

Figure 6. Foundation scheme and piles.
There are two main factors that have an important influence on the seismic response of buildings: one is the period of the structure and the other is the damping ratio. The stiffness of Pombalino buildings is large and the period is short, and its basic period is just in the frequency band of the largest earthquake input energy. As for the damping ratio of the structure, if it continues to increase, the acceleration response will continue to weaken, and the displacement response will also be significantly reduced. The larger displacement can be provided by the isolation layer between the bottom of the upper structure and the top of the foundation, not by the relative displacement of the upper structure itself. In this way, the upper structure will move close to translation during the earthquake, which greatly improves the safety of the upper structure.

The isolation layer of laminated rubber bearing base isolation system is composed of several isolators. The isolator includes laminated rubber pad and damper, which can be divided into ordinary laminated rubber pad, lead rubber pad and high damping rubber pad. This isolation system has long period, large damping ratio and obvious isolation effect. Especially, the latter two isolators do not need additional dampers, so it is convenient for construction. In many base isolation systems, through a number of experiments and studies, according to the international evaluation standards of isolation system, laminated rubber pad isolation system has the following performance advantages.

Firstly, the vertical bearing capacity of the system is large. Generally, the design value of the vertical bearing capacity of a single isolator can reach thousands of tons, and the ultimate bearing capacity can reach tens of thousands of tons.

Secondly, the isolation layer of the system has a stable elastic reset function, which can automatically and instantaneously reset in multiple earthquakes, which is completely incomparable with the friction sliding isolation system.

Thirdly, the isolator has good durability, low cycle fatigue resistance, hot air aging resistance, ozone aging resistance, acid resistance and water resistance. The service life of the product is 60-80 years through various performance tests.

Fourthly, laminated rubber pad isolation system has good isolation effect. The acceleration response of the isolated structure is much lower than that of the non-isolated. Besides, compared with other isolation systems, the influence of uneven settlement of foundation is not obvious, and the structure is simple, the installation is convenient, and the force transmission mode is simple and clear. In this paper, three approaches are mentioned to improve the seismic performance of ‘Pombalino’ buildings. The first approach is strengthening the connection between different timber members and between timber members and masonry with components made of FRP materials, which overcome many problems of the metallic elements. The second approach is using carbon fiber sheet to improve the shear strength of
the old masonry. The third solution to enhance the seismic performance and strengthen the foundation is constructing the laminated rubber pad isolation system. Besides, the construction scheme should consider the historical value and the function of the ‘Pombalino’ buildings.

5. Conclusion
In this paper, three approaches are mentioned to improve the seismic performance of ‘Pombalino’ buildings. The first approach is strengthening the connection between different timber members and between timber members and masonry with FRP materials elements which overcome many problems of the metallic elements. The second approach is using carbon fiber sheet to improve the shear strength of the old masonry. The third solution to enhance the seismic performance and strengthen the foundation is constructing the laminated rubber pad isolation system. Besides, the construction scheme should consider the historical value and the function of the ‘Pombalino’ buildings.

However, these suggestions are only based on theoretical analysis. The absence of experimental operation and field investigation leads to some questions and limits. The specific construction schemes, which should include the size and shape of the connection elements, the installation modes, the construction method of carbon fiber sheets and laminated rubber pad isolation system, can not be described in this paper. All these factors should be further discussed. In addition, the mechanical performance of FRP elements and the seismic performance of laminated rubber bearing base isolation system should be discussed in experimental operation to accommodate Pombalino buildings.

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References
[1] Lopes, M., Meireles, H., Cattari, S., Bento R. & Lagomarsino, S. (2014). Pombalino Constructions: Description and Seismic Assessment. Structural Rehabilitation of Old Buildings, vol. 2, pp. 187-233.
[2] Cardoso, R., Lopes, M., Bento, R. (2004). Earthquake resistant structures of Portuguese old Pombalino' Buildings. In: 13th World Conference on Earthquake Engineering. Vancouver, B.C., Canada. Paper no.918.
[3] Kouris, L.A.S., Meireles, H., Bento, R. & Kappos, A.J. (2014). Simple and complex modelling of timber-framed masonry walls in Pombalino buildings. Bulletin of Earthquake Engineering, vol.12, pp. 1777-1803.
[4] Zhongqing Jianzhu. Accessed on 1 August 2020. Retrieved from: http://www.gdzhongqing.cn/dgweb_content-832186.html.
[5] Matsagar, V., Jangid, R.S. (2008). Base Isolation for Seismic Retrofitting of Structures Practice Periodical on Structural Design and Construction.