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Strengthening of Masonry Buildings by Post-Stressing: The Verticalisation Method

A. Morais and S. Sazedj
Department of Technology and Management of Construction
Faculty of Architecture, Technical University of Lisbon, Portugal

Abstract

The use of pre-stressed cables for the strengthening of masonry structures is studied in this research. This technique introduces minimal changes in the characteristics of the structural system and in the visible form of the building. This paper resumes the results of an extensive parametric research and a number of numerical simulations. One of the results is the development of a mechanical model combined with a program based on the finite element method for numerically studying the behaviour of the horizontal joints between the bricks. The pre-stressed elements cause compressive forces in the masonry wall that consequently lead to the so-called "verticalisation" of load in the wall, thus reducing the strength of the horizontal load that destabilises the masonry wall.

Keyword: pre-stressed cable, reinforced masonry, arch failure, buttress, flying buttress.

1 Introduction

The societies are increasingly motivated and committed to preserving its history and its heritage. This attitude has allowed and has boosted the performance of various measures of conservation, restoration, protection and enhancement of the built heritage of the testimonies of the past. Political power has also developed policies converged with this desire and culture of civil society [1].

The sustainability of a society depends also on cultural properties that it owns; they play an important role in the promotion and enhancement of creativity, stimulating the economic growth [2].

The recovery work in structural masonry buildings, with or without mortar joints, is almost always accompanied by the question of the authenticity of the corrective action to consider. Maintaining the purity of the initial design and building is a feature valued by societies in the cultural plan. The corrections to recover the buildings, in many cases, are of a visible type, so that changes are done in the initial form of the construction. This issue becomes particularly important in the case of intervention of recovery of the National Heritage.

With the aim to contribute to the collective effort for the protection of Heritage Buildings and to participate in the economic, social and cultural development of the society it emerged the motivation to undertake a research in the field of rehabilitation of historic buildings. This paper presents a study on a possible model of application with the support of a computer program developed for this purpose.

The analytical treatment of this kind of buildings, on the structural level, presents some difficulties, given by the complexity of the mechanical phenomenology involved in these structures, where the joint between blocks affects appreciably the behaviour of masonry in structural terms. Moreover, the mathematical treatment of this phenomenology is complex because of the presence of the joint. In order to enhance the recovery work in buildings of masonry, it has been developed a mechanical model, as mentioned before, that treats this phenomenology and on basis of the finite element method a specific computer program analyses structural masonry buildings with or without structural joints.

The developed model has the great advantage of considering the mechanical behaviour and analysing the horizontal joint between the building blocks of the masonry. This possibility, of numerical treatment, brings considerable advantage, since it is a more realistic modelling of the phenomenology involved in the actual behaviour of masonry with joints filled or not. Another feature of the model relates to the analysing of the seismic behaviour, having been chosen to perform in the program step by step integration of seismic excitation. In another paper will be presented the fundaments and assumptions used in the formulation and development of this model.

This paper, based on the developed analytical finite element model, presents a methodology for possible action for the recovery of buildings, where the corrective structural reinforcement considered does not change the original architectural design of the building. The tested reinforcement consists of application of pre-stressed steel elements within the masonry. The pre-stressing causes compressive forces in the brick wall which results in a so called "verticalisation" of the existing load, by reducing the destabilizing horizontal components of forces on the bricks of the wall [3].

2 Structural phenomenology involved

The stability of the brick walls with joints not filled with mortar is essentially dependent of two parameters: i) the inclination of the force transmitted by the ceiling and the upper floors; ii) the resultant value of the vertical component of force acting on each individual block of the masonry. The inclination of the force that acts on the block is a parameter responsible for a higher or lower value of the counter force (horizontal component of force that acts on the wall) [2].

This destabilizing force can cause the displacement of individual blocks of the wall, either by rotation or by horizontal movement. In the recovery work, many of the problems of masonry are associated with a poor counter balance force, since it may take an inclined direction in the outer wall, which can result in opening of slits and possible rotation or displacement of blocks. An effectively balancing of the strength of a counter force is vital for the safety and durability of masonry and is obviously the main objective to be achieved in any restoration project.

There are several reasons that provoke the counter force, after some time, sometimes centuries, to create problems in the structural construction performance, in terms of either security or functionality. However, the four major causes relate to possible settlements of foundation, the permanent deformation due to thermal and hygrometric action, increase of the overload acting on the building, and finally due to poor initial formal concepts (incorrect geometric proportions).

In the course of time to deal with the effects of the imbalanced counter force various techniques have been adopted, as appropriate and in accordance with the practice and technology of time. But not always existed theoretical support for the repair solutions. The design was based more on empirical methods based on experience and not on the quantification of the actuating forces and stresses.

The recovery work consists commonly of the following applications: the introduction of stiffness walls, which provides an increase of the structural section; the connection of the two outer walls with a rod that self-balances the internal counter forces; the addition of a buttress producing a direct equilibrium (structural systems where the internal work of the bending moment is not present); the addition of a independent reticulated structure; the implementation of reinforcements on specific points of the structure (sometimes reinforced concrete); and sometimes the placement of elements of heavy weight (like statues on top of the walls), which force the actuating load to a upright position in the wall, in order to reduce its inclination, thereby reducing the destabilizing horizontal component (the counter force).

The usual solutions referred above to recover masonry have a strong disadvantage. They modify the interior and exterior form of the building and are controversial regarding the authenticity and purity of the original architecture.

3 The reinforcing solution, to upright the acting load

Enhanced by the mechanical model developed, the technique presented in this paper allows creating solutions where a formal modification of the authenticity of the building does not occur. If pre-stressed cables are introduced into the masonry wall, structurally reinforcing it and being invisible, thus they do not alter the shape of the initial building. The pre-stressing by compressing the masonry has the same effect of to upright a load by raising the load through additional materials (statues and lane gifts at the top of the masonry wall of the Gothic period). It is therefore a solution to be adopted when it is meant to maintain the formal exterior and interior of the building to be recovered [4].

The solution to introduce pre-stressed steel cables in the masonry, sealed with mortar or other sealant, will upright actuating loads and endows the masonry wall with additional shear strength and reinforces the seismic resistance of buildings in structural masonry. The vertical component of force that acts on the masonry wall has a key role in the stability of the wall, when horizontal forces are acting on the building, in particular seismic forces.

The displacement of a brick caused by a horizontal force, depends mainly on the friction between surfaces of the bricks and the size of the vertical component of force acting in the masonry structure. The greater the vertical force component the greater will be the tangential friction between the bricks, thus hindering the displacement, horizontal movement or rotation, of the brick and increasing the moment of stabilization and the steering effort to upright the internal force. This effect of decreasing the inclination of the internal force to the vertical axis of the wall is named the "verticalisation" of the force as shown in Figure 1. It can be achieved by applying additional vertical external load, through the introduction of pre-stressed cables.

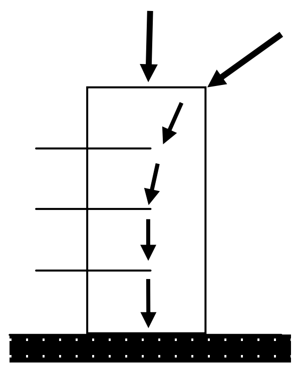


Figure 1: The "verticalisation" of load

Complementary, the addition of artificial external load through the pre-stressed force causes an increased compression on the horizontal joints between the bricks and, as a result, increases the friction between the bricks in the horizontal joints. This technique seeks to take advantage of Coulomb's friction like behaviour of the horizontal joints between the blocks of the brick wall. This effect provides a very significant increase in resistance of horizontal forces, in particular of seismic origin, thereby contributing to increasing the strength and stability of the masonry structure.

In old masonry buildings with joints without mortar, structural damages as slits are observed to be more or less open, due to displacement and rotation of bricks. The structural reinforcement with pre-stressed cables permits to close the joints and the repositioning of the bricks.

In addition to the "verticalisation" of internal forces and closing of joints, the pre-stressed cables absorb stresses that have settled, whatever their direction may be; they improve the flow of internal forces through the brick wall to the foundation by permitting a direct transfer of the internal forces; they correct the possible eccentricity of the forces and thereby prevent bending, which is very important for masonry with mortar joints and increases significantly the earthquake resistance of a structure.

Since the walls of masonry structures of this type have always thicknesses exceeding 40 cm, an insertion opening with 5-6 cm in diameter inside the walls and columns is perfectly possible, without causing local disruption in the material of the blocks. Within these openings the pre-stressed steel cables, continuously and anchored on both sides, are placed.

4 The case of application – Church of Santa Maria

4.1 The current constructive problem

With the help of the mechanical model and the subsequently developed computer program stability studies of masonry buildings and analyses of recovery solutions have been carried out by introducing structural pre-stressed cables.

A very interesting case that has been studied was the church of Santa María la Real de Sar Y Mayor, on the outskirts of Santiago de Compostela, located along the river Sar in Spain, Figure 2. The construction of this monument began in 1134 and on 14 August 1895 was considered a National Monument having suffered throughout its history various repairs and restoration by the Spanish General Directorate for National Buildings and Monuments.

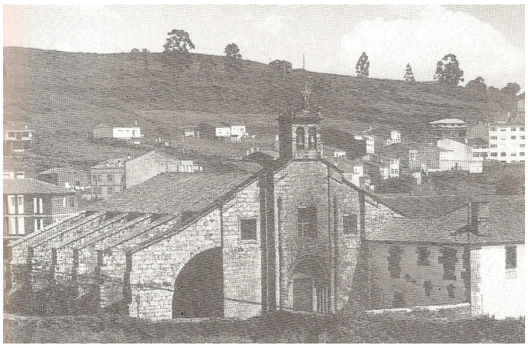


Figure 2: Church of *Santa María la Real de Sar Y Mayor*

This monument is famous due to the slope of the interior columns and exterior walls, giving visitors the impression that the arcs of coverage tend to fall apart. In the 16th century the inclination of the walls and columns reached high values, which led to the collapse of the central arch, Figure 3.

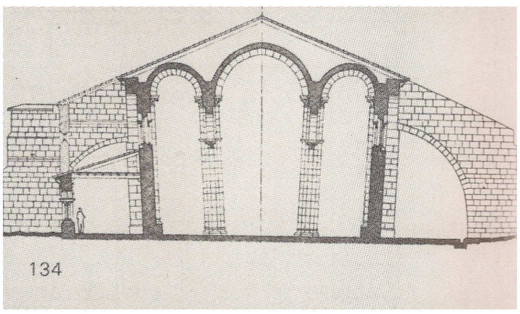


Figure 3: Drawing of the arch

In the reconstruction of the church the central arch remained supported on bowed columns and walls, but to provide the stability that had been missed earlier and that caused the collapse, exterior buttresses were constructed, with very high dimensions as the Figures 4 and 5 illustrate.

Figure 4: Configuration of the buttresses

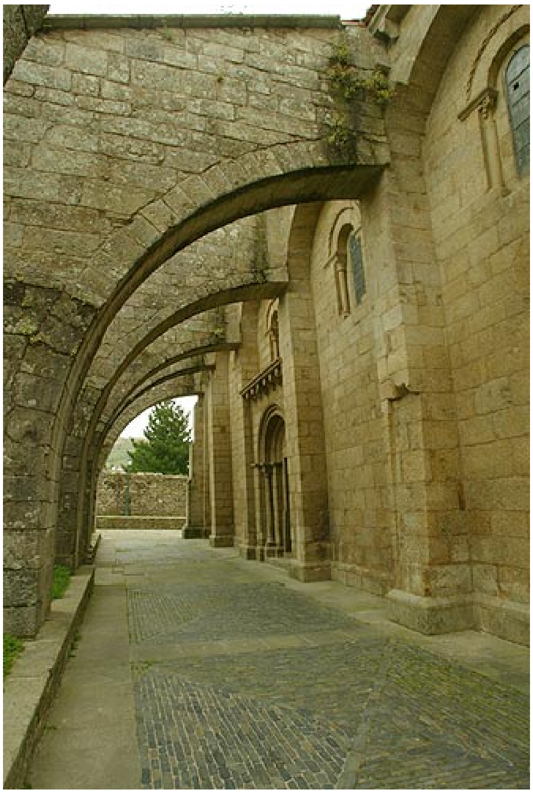


Figure 5: Image of the dimensions of buttresses

These buttresses balance and transfer counter force to the outside, in direct balance by preventing destabilization through the lateral arms. The pillars inside the church still remain inclined, as shown in the accompanying figure. The instability of the church of Santa Maria de Sar was due to poor design of formal arcs of aisles shown in Figure 6.

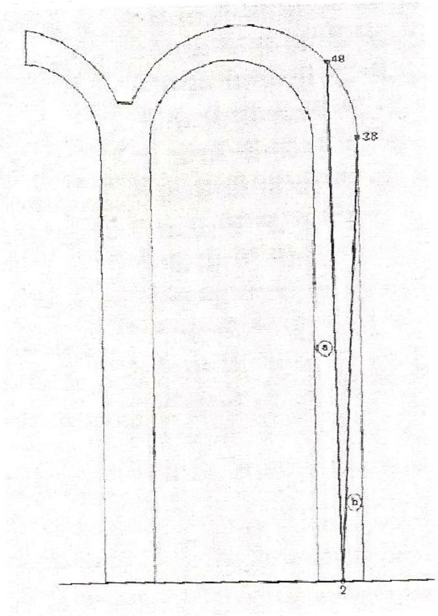
Figure 6: Image of the columns

This construction does not follow the usual rules of proportionality used for this kind of building, since they are placed side circular arcs on a too high quota, compared to the central arch. With this geometrical proportion in construction, and with a under designed size of stiffness walls, side arches failed to counter balance the forces developed by the central arch and evidently the collapse succeeded.

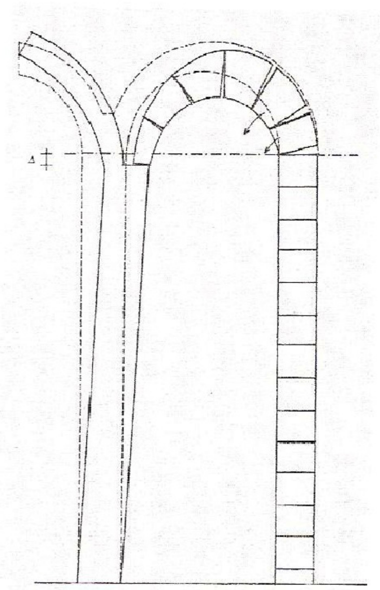
With the mechanical model and the software developed it was possible to analyse the structure of the initial configuration of the church and then to study the repair on bases of a solution with pre-stressed steel cables. Aim of this study, in addition to test the application of the developed model, is to show that it is possible to repair a church without the need of the construction of flying buttresses, in other words without changing the shape of the building.

From the results obtained it appears categorically that the initial geometry of the monument was not stable and therefore it is very likely and expected to occur the verified collapse.

The study shows that a possible solution to repair this building, aiming at the stability of the blocks, is the application of three pre-stressed cables, one in each column as demonstrated in Figures 7 and 8. It is considered in the analysis that the arches are plane, a hypothesis reproducing with some rigor the physical and formal reality of the building.



Figures 7: Localization for the pre-stressed cables



Figures 8: Recovery through the pre-stressed cables

The rupture of the structure of the arcs leads immediately to the third interaction, joint number 26, which completely breaks under tensile stress. That is, the idealized blocks number 5 of the finite elements net developed moves to the block number 4, eventually collapsing inside the building, designed in Figure 9.

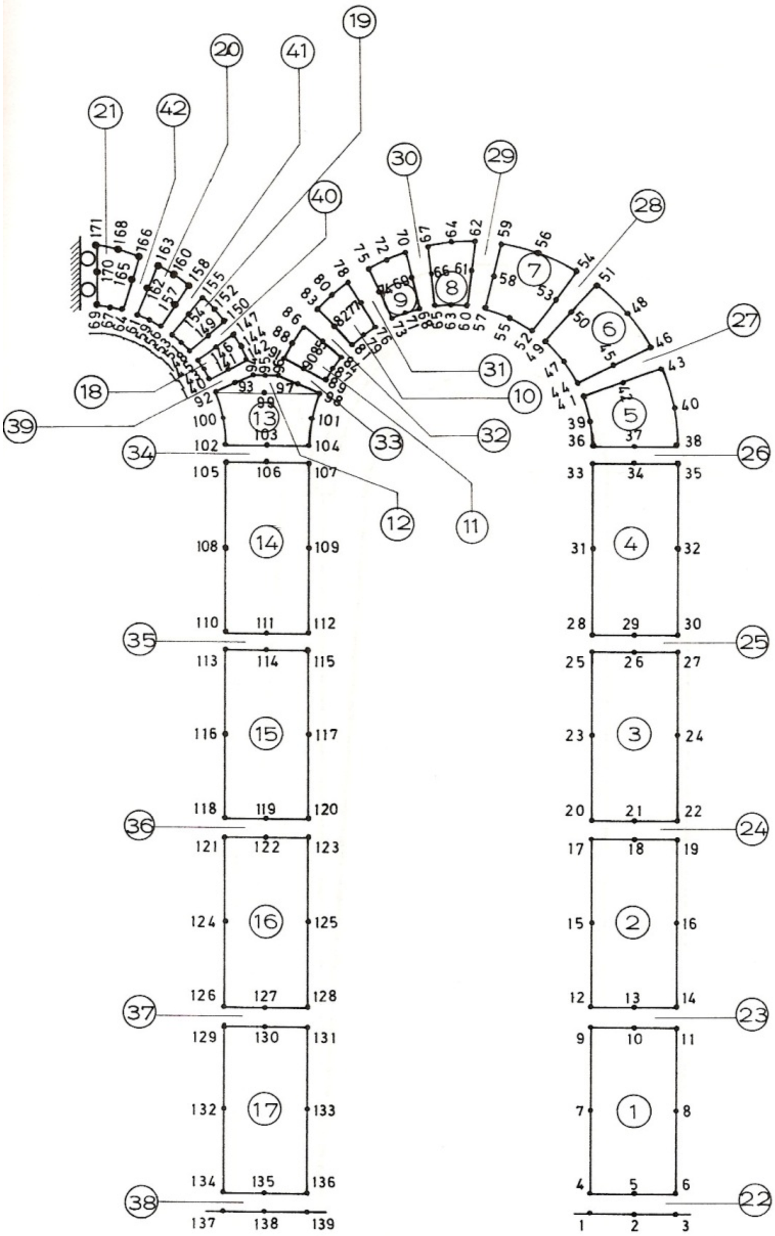


Figure 9, Numbering of the arch blocks

Through the analysis of the results obtained, it is observed that if the top of the column system moves to the right, it imposes a horizontal force to the side arch. Furthermore, at the insertion of it with the central arch, causes a rotational movement of the blocks of the side arch. Such movements cause a shift in the direction of the force, which is transmitted by each block to the next block, therefore the arch joints open, and reduce the contact area between the blocks. Finally comes the point where the transmission of load takes place only in one point, then, as is the case of the passage of block 6 to 7, the load transmitted has a destabilizing direction, as it is not inserted into the block 6, forcing it to rotate and flipping into the inside of the building.

Obviously after fracture of the side arch the joint no. 34 fails by shear force, befalling also the collapse of the central arch. The middle column and also the lateral column do not fail, because after the collapse of the arches they are only subject to their own weights and the direction of the resultant force that is now placed within the section of the blocks, despite the inclination of the central column.

Hereby is proven that the mechanical model developed confirms the geometric error committed in the initial formal design of the church, thus justifying the structural failure the building suffered.

4.2 Analyses of the experimented solution

In the recovery of the church *Santa Maria de Sar*, with the aim of correcting the initial formal anomaly, flying buttresses were laterally added in the continuation of the frame of the central and side naves. These buttresses carry in a balanced way directly the counter load developed by the central arch to the outside of the building. With this formal solution the repair of the problem of instability of the arches that the church had with its original design, was resolved. However, with this solution, as seen in the figures, the form of the building has changed completely, in particular its urban integration.

Though, the solution of reinforcement by pre-stressed cables allows correcting the anomaly of the initial design of the church, without the need to change the shape and the architecture of the church.

In this study regarding the side arches, two solutions were tested for possible locations of the reinforcement with wire ropes as shown in Figure 7, only half of the structure. For the central arch, it was studied a single solution for location of the cables, which also is shown in the same figure. Here the cables are inserted according to the axes of the columns of the central arch support.

The side arches, in one solution, the cable connects nodes 2 and 48, while in another solution, the cable ends are nodes 2 and 38 shown in Figure 9. The finite element network used to study the reinforcing is exactly the same with which is performed the structural analysis of the initial form. The cables are pre-stressed in both reinforcement solutions, with loads of 10 and 50 kN, respectively for the central and side arches. Obviously, other combinations of load are possible. The results of calculations, performed for failure, demonstrate that with the insertion of pre-stressing, in both solutions of reinforcement, it is possible to stabilize the initial form of the church of Santa Maria de Sar.

5 Conclusion

The study made shows that the mechanical model developed with its finite element program allows us to analyse structural masonry buildings, with and without mortared joints.

This model is particularly arranged and recommended to use for the support and development of methods for reinforcement and recovery in order to maintain the purity of form of historic buildings, by inserting pre-stressed steel cables in walls.

It was studied an application of the developed model and the technical feasibility of using the proposed solution in a case of recovery of the church of Santa Maria de Sar, where the structure because of errors in their initial geometric proportions collapsed and required repairs.

It could be proven that the recovery of fractured masonry of historic buildings with pre-stressed steel ropes and cables is applicable without adding any visible elements, hereby maintaining the authenticity of the initial architectural form.

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