Seismic strengthening of masonry buildings with reinforced concrete floor slabs: the schools D. João de Castro and Sá da Bandeira - Portugal

António Sousa Gago & Jorge Miguel Proença
Technical University of Lisbon - Instituto Superior Técnico (Portugal)

Miguel Villar
Betar, SA (Portugal)

15 WCEE
LISBOA 2012

SUMMARY:
In Portugal, as in many other earthquake prone regions, buildings with unreinforced masonry load bearing walls represent a significant percentage of the building stock at risk due to earthquakes. These buildings can be divided into two categories, depending on the floor structure type: timber floors or reinforced concrete floors. The buildings with reinforced concrete slabs supported by masonry walls were built at the last phase of the so-called *traditional construction* and are representative of the early use of reinforced concrete. This paper focuses on the structural studies (numerical and experimental) performed to support the design of the strengthening intervention carried out in two public buildings with masonry load bearing walls and reinforced concrete floor slabs: the D. João de Castro School, in Lisbon, and the Sá da Bandeira School, in Santarém. In both cases the strengthening was based on reinforced plastering mortar applied on the main wall alignments.

Keywords: Masonry, Seismic Assessment, Strengthening, Reinforced Plaster

1. INTRODUCTION

Buildings with masonry structure contribute in a very significant way to the seismic risk of Mediterranean urban areas. When subjected to earthquake loads of considerable severity these buildings present several collapse mechanisms, all of them involving the failure of masonry load bearing walls [1]. Thus, the most important feature to take into account in the seismic strengthening of old masonry buildings is the strength and ductility of the load bearing masonry walls. In the present paper a seismic strengthening solution for load bearing walls of masonry buildings with reinforced concrete slabs is presented. This type of buildings were built in Portugal and other Mediterranean countries in the 2nd and 3rd quarters of the twentieth century and are structurally characterized by reinforced concrete horizontal elements (slabs and beams) and unreinforced masonry vertical elements (walls – Fig. 1.1). In the majority of the cases, the horizontal reinforced concrete elements have satisfactory in-plane stiffness and the floor structures behave like rigid diaphragms. In some particular zones of these buildings, were large empty areas were required (like halls or covered playgrounds), reinforced concrete vertical elements (columns) can be found (Fig 1.2). However, these elements were rarely used and its local existence does affect the global structural behaviour of the building. The strengthening solution under analysis is based on the traditional reinforced plaster, in which an important improvement was introduced by anchoring the steel mesh to the (top and bottom) reinforced concrete slabs. The use of a controlled composition mortar (pre-dosed mortar based on hydraulic lime) on the execution of reinforced plaster had also improved the strength of the strengthened walls. The efficiency of the strengthening solution was verified through an experimental program, which is described in the present paper. Four masonry wall specimens were tested in situ. Two pairs of wall specimens were tested. Each pair corresponds to one of the two types of masonry typically used in this type of buildings (rubble stone masonry and concrete blocks masonry), being one specimen tested in its original state and the other after strengthening. The results indicated a significant increase of the specimen's in-plane resistance, which was due to the effect of strengthening on both surfaces of the walls.

Figure 1.1 Secondary School of D. João de Castro, in Lisbon. Left: rubble stone masonry walls; Right: concrete block masonry walls

Figure 1.2 Secondary School of D. João de Castro, in Lisbon. Left: reinforced concrete column and beams; Right: Reinforced concrete slab

The effectiveness of the strengthening solution in a real intervention was studied in two case studies: the buildings of the Secondary Schools D. João de Castro, in Lisbon, and Sá da Bandeira, in Santarém. In this paper the main conclusions of the numerical studies performed on those buildings are presented. The buildings were simulated by numerical models (linear elastic finite elements models calibrated by experimental in situ dynamic tests), which simulated the buildings behaviour under the effect of static and dynamic loads (defined in accordance with Portuguese code [2]). The analysis of the numerical results was done globally and locally, i.e., taking in to account the global strength of the building and the occurrence of local collapses. In the global point of view, considering the average values of the seismic shear stresses (in both horizontal directions), it was found that, even in the absence of strengthening, the stability of buildings would be achieved (although with widespread local collapses). The local analysis allowed identifying the locations where the seismic shear stress exceeds the shear strength, calculated by the Mohr-Coulomb criterion. This local study gave indications about the location and extent of the strengthening to be performed during the (structural and architectural) rehabilitation of the buildings.

2. DESCRIPTION OF THE STRENGTHENING SOLUTION

The proposed strengthening solution for rubble stone and concrete block load bearing masonry walls consists of a reinforced plaster based on a mortar of controlled composition (pre-dosed), incorporating a stretched galvanised steel mesh. In the study here reported the efficiency of this traditional strengthening solution for masonry walls was greatly improved by anchoring the reinforcement steel mesh to the concrete slabs of the upper and lower floors. This solution is suitable for seismic strengthening of the buildings built at the end of the first half of the twentieth century, with a structure

based on masonry walls (rubble stone or concrete block masonry) supporting horizontal reinforced concrete elements (slabs and beams). The variant of the reinforced plaster solution herein described was developed, tested and applied in two case studies with structural characteristics representative of the buildings built at the end of the first half of the twentieth century. In those buildings the bearing structure (designed to withstand vertical loads) is composed of outer thick masonry walls on rubble stone (with thicknesses greater than 60 cm), and inner masonry walls on concrete blocks, with smaller thickness (about 30 cm). The floors are made of reinforced concrete slabs, armed predominantly in one direction, which are supported by the masonry walls. The stability of these buildings depends almost entirely of the strength and ductility of the loadbearing masonry wall. Thus, special care should be given to those structural elements in any the seismic strengthening intervention. The development and characterization of the strengthening solution herein described was undertaken with that outlook. As mentioned, the strengthening is obtained by a reinforced plaster, which is placed at one or both sides of the wall, and is connected to the wall substrate by steel staples (inner walls), which pass through the entire wall thickness, or anchored by rods (thick outer walls). Moreover, the stretched steel mesh is attached to the top and bottom concrete slabs by inclined rod. The connection to the concrete slabs increases the walls shear resistance and also benefits the diaphragm effect of the slab. The details of the strengthening solution for inner (concrete blocks) and outer (rubble stone) masonry walls are shown in Fig. 2.1
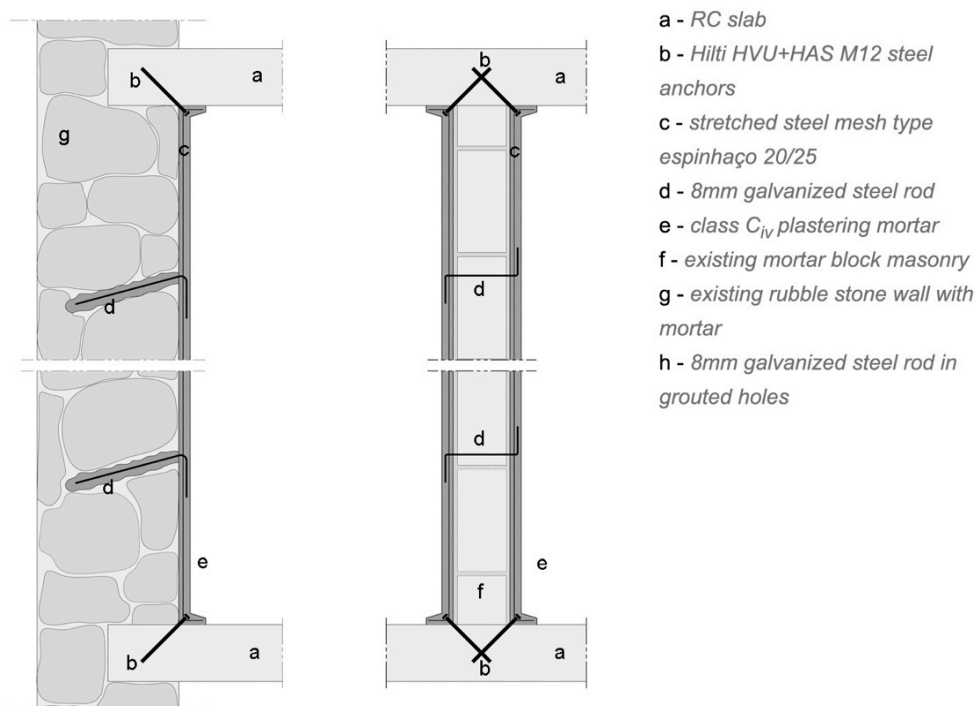

a - RC slab
b - Hilti HVU+HAS M12 steel anchors
c - stretched steel mesh type espinhaço 20/25
d - 8mm galvanized steel rod
e - class C_{iv} plastering mortar
f - existing mortar block masonry
g - existing rubble stone wall with mortar
h - 8mm galvanized steel rod in grouted holes

Figure 2.1 Strengthening solution for concrete block masonry walls (right) and rubble stone masonry walls (left)

The procedure for the wall strengthening comprises the following steps: integral removing of the original rendering; placing of the galvanized stretched steel mesh; stapling and anchoring of the steel mesh to the slabs and walls; and, finally, the application of plaster mortar (in the present case it was used a pre-dosed mortar with a minimum compressive strength of 8 MPa). The different stages of the masonry walls strengthening procedure are illustrated in Figure 2.2.

3. EXPERIMENTAL TESTS

The efficacy of the strengthening solution was assessed by experimental tests carried out in situ. As mentioned, a total of four wall specimens were tested, corresponding to the combinations of the two types of masonry walls (rubble stone and concrete block) and to the existence or non-existence of the strengthening. The tests were performed in the Secondary School D. João de Castro, taking advantage

of the walls that would be demolished in the functional rehabilitation of school buildings. The specimens were submitted to vertical and horizontal in-plane loads and were fully instrumented, with numerous displacement transducers and load cells. The corresponding experimental setup is shown in Fig. 3.1 and in Fig. 3.2. In each test was applied a vertical load corresponding to a vertical stress of 0.8 MPa, which was maintained constant during the complete test.

Figure 2.2 Strengthening solution – details of the mesh nailing and anchoring and of the mortar plaster

The applied vertical stress simulated the mean compressive stress of the masonry walls in this type of buildings. After reached the desired vertical stress level, a horizontal in-plane load was applied to the specimen. The horizontal loading was performed repeatedly, with loading and unloading branches, till the maximum strength of the specimens was reached. Table 3.1 presents the obtained values for the young modulus E in compression, as well as, the values of the maximum applied forces. It worth mention a significant increment in shear strength and shear deformation capacity of the strengthened walls, which can be identified in the "horizontal load versus horizontal displacement" diagrams (Fig. 3.3 and Fig. 3.4). The tests clearly indicate the beneficial effect of strengthening on both walls sides, which increased the in-plane resistance and reduced the damages, concentrating them at the wall base.
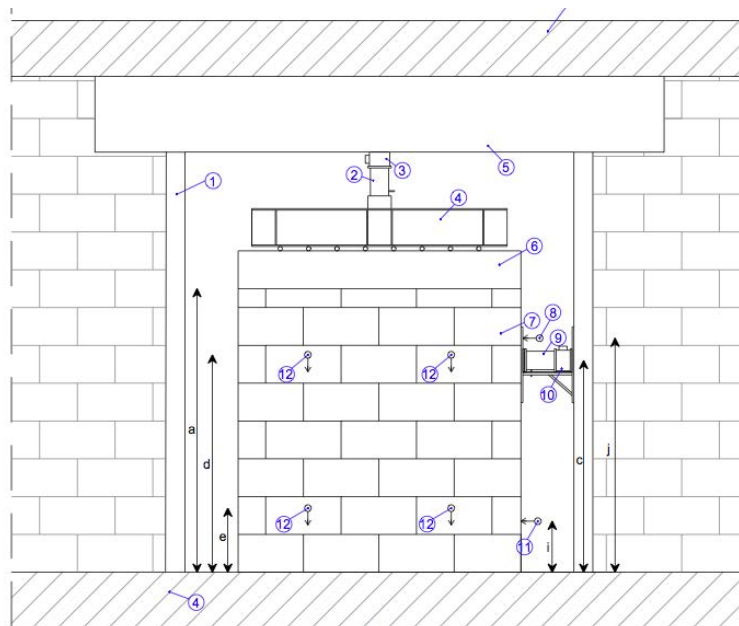

Figure 3.1 Test setup

As mention, it was also performed in situ experimental tests for dynamic characterization in the main buildings of the Secondary Schools of D. João de Castro and Sá da Bandeira. Those tests, not reported here, were used to calibrate the numerical models presented in the next chapter [3, 4, 5]. Thought not tested experimentally, the behaviour of the strengthened walls under out-of-plane loads can be evaluated taking in to account the guidelines for reinforced masonry described in the Eurocode 6 [6]. However, the bearing capacity that the strengthening solution confers on the walls for out-of-plane loading was not considered in the safety assessment studies that are presented in the following paragraph.

Figure 3.1 Test setup (left) and general view of a concrete block specimen (centre) and of a rubble stone specimen (right)
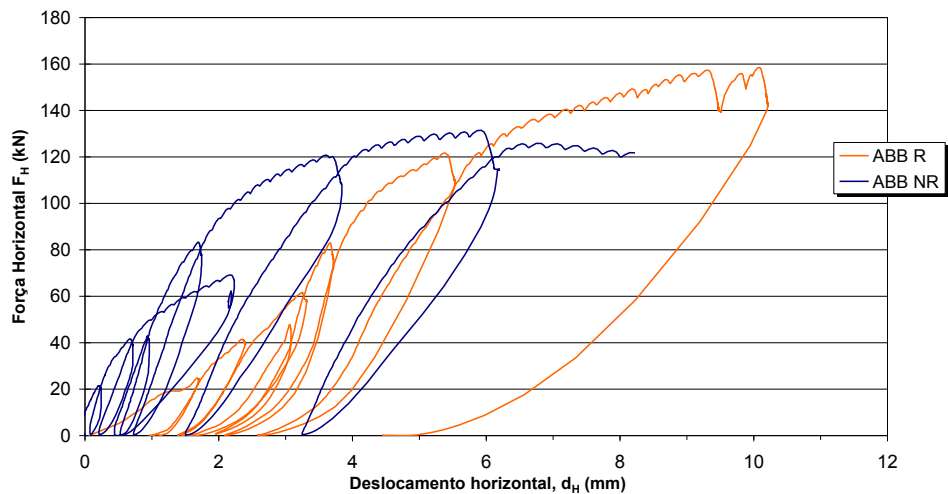

Figure 3.3 Force-Displacement diagrams for the concrete block masonry specimens – R: reinforced specimen; NR: non reinforced specimen
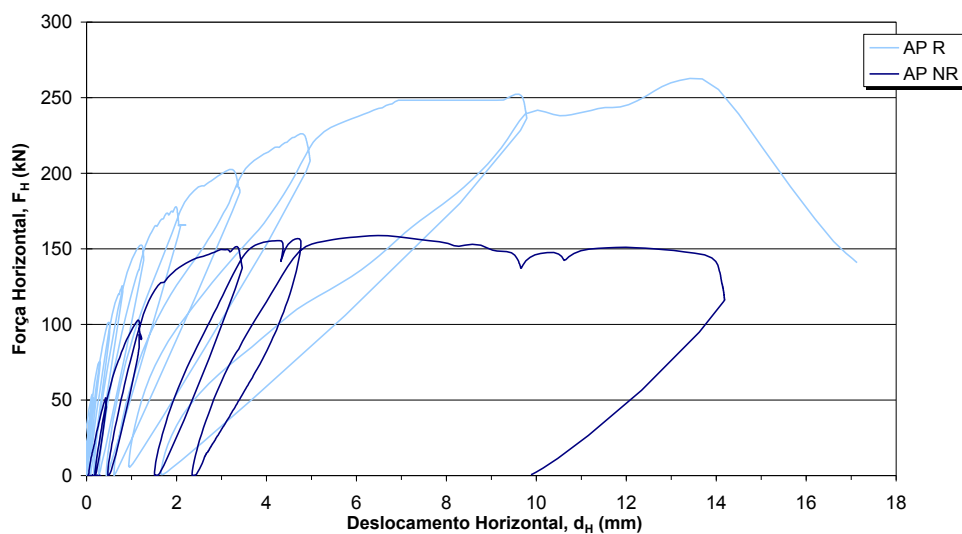

Figure 3.4 Force-Displacement diagrams for the rubble stone masonry specimens (right) – R: reinforced

specimen; NR: non reinforced specimen

Table 3.1. Experimental Results

Specimens		A (m2)	Maximum Vertical Force	Maximum Horizontal Force	E (GPa)
Concrete Block Masonry	non- reinforced	1.50x0.20	230 kN	132 kN	2.20
	reinforced	1.50x0.20	223 kN	158 kN	2.40
Rubble Stone Masonry	non- reinforced	1.05x0.48	415 kN	159 kN	2.00
	reinforced	0.98x0.48	505 kN	263 kN	2.30

4. CASE STUDIES - SECONDARY SCHOOLS OF D. JOÃO DE CASTRO AND SÁ DA BANDEIRA

The promising test results led to adopt the present strengthening solution in the seismic strengthening of the loadbearing masonry walls of the Secondary Schools of D. João de Castro, in Lisbon, and Sá da Bandeira, in Santarém. It was intended to obtain by the study and by the implementation of the strengthening solution in these two case studies, experience and standardized procedures to be used in other school buildings with analogous structural systems. In both cases the strengthening of the loadbearing masonry walls was focused on the critical walls to the equilibrium of the whole building. For that, linear elastic finite elements numerical models were built (Fig. 4.1), which helped to identify the more stressed walls in the case of a seismic event. In the finite element models the masonry walls and the reinforced concrete slabs were simulated by four nodes shell elements, with membrane and flexural behaviour. The membrane behaviour was adopted on the slab shell elements to simulate the diaphragm effect of the pavements. The beams and the (rare) columns were simulated by beam elements. A linear elastic behaviour was assumed for all elements and the mechanic characteristics were obtained by calibration of the numerical dynamic characteristics. The numerical fundamental modes of vibration and respectively frequencies (Fig. 4.2) were calibrated with the experimental results, which led to a 2.0 GPa Young modulus for rubble stone masonry and concrete block masonry elements, in the case of the D. João de Castro Scholl; and to a 2.5 GPa Young modulus, also for both types of masonry, in the case of the Sá da Bandeira Scholl. For concrete elements a 29 GPa Young modulus was adopted in both cases. In the seismic analysis a behaviour factor of 1.5 was adopted. To model the unidirectional behavior of the reinforced concrete slabs, the correspondent plate shell elements were defined with different bending stiffness in the two horizontal directions. For the seismic action, the two kinds of earthquakes specified by the Portuguese code [2] were considered. The respective response spectra used were quantified for a damping coefficient of 5%.
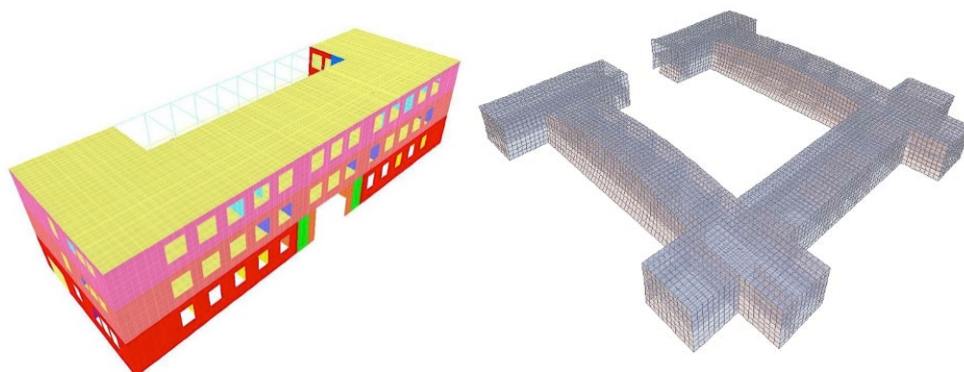

Figure 4.1 Finite Element Models – Left: D. João de Castro School; Right: Sá da Bandeira School

The numerical models were used to evaluate the vertical stresses on the masonry walls due to dead loads and the shear stresses on the masonry walls due to the earthquake loading (Fig. 4.3). The numerical results for the earthquake loading (defined in accordance with the Portuguese code) were

analysed through a global and a local perspective. In the global point of view, the resultant horizontal seismic force, in both directions, was divided by the walls total cross-sectional area, in the direction under analysis, which was compared to the mean shear stress strength, evaluated from the dead load vertical stress (obtained dividing the vertical resultant by the walls total cross-sectional area) by a Mohr-Coulomb criterion. For the Mohr-Coulomb criterion and for both types of masonry walls, a characteristic value of 0.50 was assumed for the friction coefficient. For the cohesion and also for the both types of masonry walls, the characteristic values adopted for unreinforced and reinforced walls were, respectively, 0.02 MPa and 0.25 MPa.

The global analysis of the D. João de Castro and Sá da Bandeira Schools showed that in the absence of the strengthening the buildings presented, globally, enough strength to support the seismic load. However, the local analysis, where the seismic shear stress and the shear strength are compared in each integration point, led to the conclusion that the strengthening must be done to avoid the extensive local collapses. Fig.4.4 shows the results of the analysis performed in one of the loadbearing walls, where two possibilities were studied: with or without strengthening. As it can be seen in Fig. 4.4 with the strengthening (which was incorporated in the numerical study by a bigger cohesion) the situations of local collapse declined significantly and are located on areas of reduced axial forces (e.g. beneath the windows and on top of the roof). Thus, if in both buildings the longitudinal inner and outer walls, which support the floor slabs, and some transversal walls are reinforced, the structural integrity of the buildings will not bee compromised during an earthquake. However, some local damages can occur.
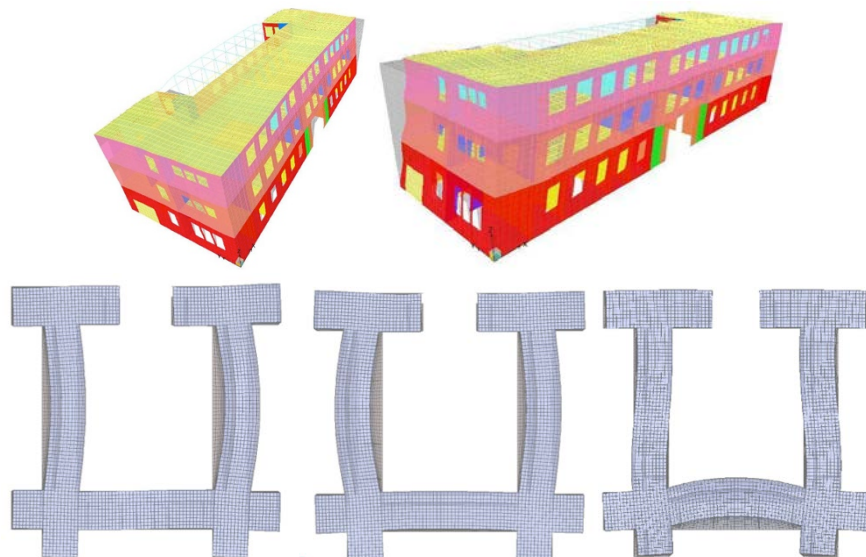

Figure 4.2 Numerical Models –modes of vibration: D. João de Castro School (TOP) 1st mode (4.9Hz) and 2nd mode (5.6 Hz); Sá da Bandeira School (BOTTOM) 1st mode (8.3 Hz), 2nd mode (8.4 Hz) and 5th mode (10.7 Hz)
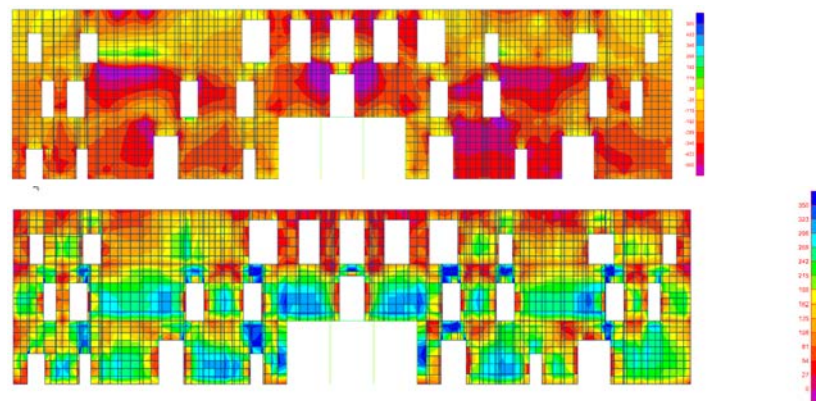

Figure 4.3 D. João de Castro School - Numerical Model: vertical stresses due to dead loads (TOP) and shear stress due to the seismic load (BOTTOM) on the main façade
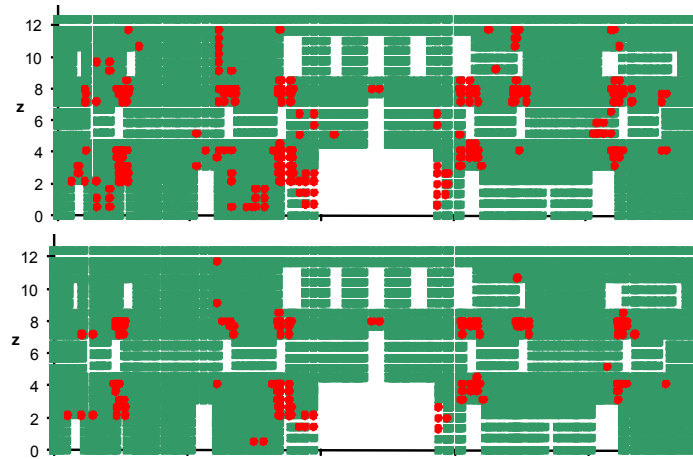
Figure 4.4 D. João de Castro School - Numerical Model: diagram indicating the points where the seismic shear stress exceeds (in red) or not (green) shear strength (TOP: unreinforced wall; BOTTOM: reinforced wall).

In addition to the strengthening of the loadbearing masonry walls other strengthening measures were undertaken. The external rubble stone masonry walls were fixed by anchors to the roof slabs (Fig. 4.5), the gables were reinforced (Fig. 4.5) and the reinforced concrete columns were strengthening by jacketing.
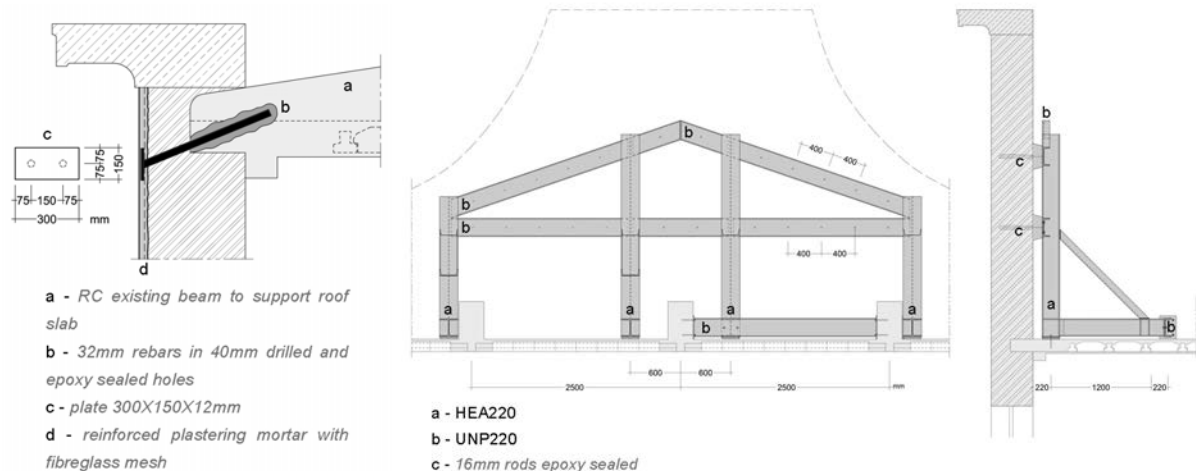

a - RC existing beam to support roof slab

b - 32mm rebars in 40mm drilled and epoxy sealed holes

c - plate 300X150X12mm

d - reinforced plastering mortar with fibreglass mesh

a - HEA220

b - UNP220

c - 16mm rods epoxy sealed

Figure 4.5 Details of the connection between the rubble stone external walls to the roof slab (left) and of the gable stabilising structure (right)

5. CONCLUSIONS

In this paper a strengthening solution for loadbearing masonry walls is presented. The solution was tested in the scope of two interventions in masonry buildings built at the end of the first half of the twentieth century – the Secondary Schools of D. João de Castro and Sá da Bandeira, in Portugal. Those buildings are structurally characterized by reinforced concrete horizontal elements (slabs and beams) and unreinforced masonry vertical elements (masonry walls). The strengthening solution under analysis is based on the traditional reinforced plaster in which an important improvement was introduced by anchoring the steel mesh to the (top and bottom) reinforced concrete slabs. The efficiency of the strengthening solution was verified through an experimental program performed in situ on four masonry specimens. During the tests the strengthened specimens presented a significant increase in strength and ductility when submitted to in-plane loads. The out-of-plane behaviour was not tested; nevertheless a substantial increase of strength is also expected. In addition to the good

results obtained in terms of mechanical behaviour, the good performance of the strengthening solution in terms of its implementation and of its cost must be stressed. In fact, in the two described interventions (D. João de Castro e Sá da Bandeira Schools) the application of the strengthening was easy and fast, resulting in reasonable strengthening costs. It should be noted that in some locations of the two buildings studied, the removal of original plaster walls already included in the rehabilitation program, which decreased the extra cost of the seismic strengthening intervention.

Linear elastic finite element models were used to perform the seismic assessment of the studied buildings. It is well known that the material model used (linear elastic) doesn't simulate properly the behaviour of unreinforced load bearing masonry walls. However, important conclusions can be reached with this type of models if an appropriate approach is used. In most of the cases the designers do not have finite elements codes providing non-linear analysis and even if they have it, the numerical difficulties disable global studies of large buildings. Non-linear analyses are mostly used in research and in the study of local problems. Thus, a procedure to study the results of linear elastic models, providing guidelines for the seismic assessment of old masonry buildings, would be welcomed by the designers. In this paper two cases studies where global and local analyses were performed (based on linear elastic models) are shown, in order to assess the seismic safety of the buildings. The models showed the need to strengthen these buildings and the locations where most attention should be given in the design of the seismic strengthening solution.

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