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Proposal for interventions in a single-family building subject to seismic actions

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***Abstract* – This paper presents a structural analysis and intervention proposal for a single-family masonry building from 1930 located in Setúbal, Portugal, subjected to seismic actions defined by Eurocode 8. Linear dynamic analysis using SAP2000 identified critical areas with excessive tensile and shear stresses, particularly in interior walls and around openings. Based on ICOMOS principles, three reinforcement strategies were proposed: reinforced plaster, metallic rods, and injection with synthetic mesh. Each method aims to enhance the masonry's tensile and shear strength while maintaining reversibility and material compatibility.**

Keywords – masonry, seismic reinforcement, structural rehabilitation, tensile and shear strength.

1. INTRODUCTION

This report consists of applying seismic actions to a single-family building in order to determine the areas of fragility that need to be reinforced.It should be noted that this building is a residential building dating from 1930, located in Setúbal. The structural elements are made of masonry, with the exception of the concrete slabs.

The seismic analysis will be performed for both seismic actions, types 1 and 2, using a linear dynamic analysis that will determine the forces/deformations, allowing us to identify the area with greater fragility and find solutions for it. In addition, a deformation analysis will be performed using an automatic calculation program. The study will be carried out using the SAP2000 program.

As described above, the building dates back to 1930 and has two floors: ground floor and first floor. The ground floor consisted of five rooms: a living room, two bedrooms, a kitchen, and a kitchenette. The first floor, which is accessed via a staircase from the living room, consists of two bedrooms and a storage room. It should be noted that the ground floor plan provided does not indicate the location of the bathrooms, although the authors acknowledge that such rooms existed.

Regarding the materials used in the building, the information provided is as follows:

- Exterior walls made of ordinary mortar masonry (limestone);
- Interior walls made of solid ceramic brick masonry;
- 10 cm thick concrete floors;

- Pine wood roof structure;
- Ceramic tile roof with paneling and thatch.

In addition, the building has a ground floor height of 3.00 meters, with 2.00-meter-high doors and a 0.90-meter window. It is worth noting that the authors did not specify whether the building underwent any material changes or whether there was any structural intervention.

Furthermore, the building is located in the city of Setúbal, on land classified as type A, which, according to Table 3.1 Eurocode 8-1, is rocky terrain that includes a maximum of 5 meters of weaker material on the surface.

2. LINEAR DYNAMIC ANALYSIS

The analysis will be based solely on the application of seismic loads, without taking into account actions such as wind, as this is a small building with walls 70 cm thick and therefore not subject to wind loads.

EC8-1 provides for two types of earthquakes with the respective accelerations for areas in Portugal, which are referred to in Figure 1 and Figure 2, respectively.

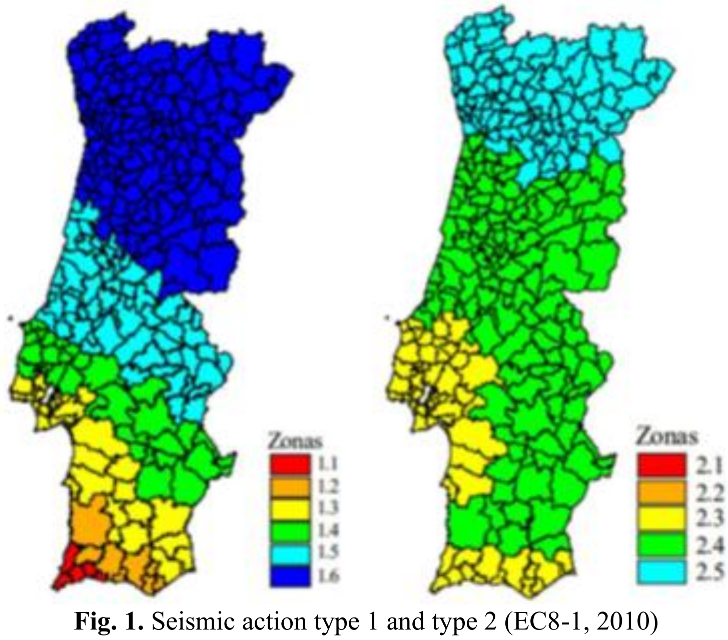

Fig. 1. Seismic action type 1 and type 2 (EC8-1, 2010)

As mentioned above, the region under study is Setúbal and therefore falls within zones 1.3 and 2.3 for type 1 and 2 earthquakes, which also determines the following maximum reference accelerations:

- Seismic zone 1.3 - a_{gR} = 1,50 m/s^2
- Seismic zone 2.3 - a_{gR} = 1,70 m/s^2

In addition, the values of the defining parameters of the elastic response spectrum for seismic action type 1 and type 2, respectively, are as follows:

Table. 1. Values of the elastic response spectrum parameters for seismic action of seismic action type 1

Terrain type	S max	T_B (s)	T_C (s)	T_D (s)
A	1,00	0,10	0,60	2,00

Table. 2. Values of the elastic response spectrum parameters for seismic action of seismic action type 2

Terrain type	S max	T_B (s)	T_C (s)	T_D (s)
A	1,00	0,10	0,25	2,00

For the last two calculation variables of the spectrum, called β (the coefficient corresponding to the lower limit of the horizontal calculation spectrum) and q (the behavior coefficient), the values taken into account are 0.2 and 1, respectively.

The combinations used in the model are based on the equations provided by Eurocode 0, with three types of combinations being used in practice:

a) fundamental, of the ultimate limit state;
b) seismic, where the actions of the two types of earthquakes in the two directions are considered;
c) wrapping combination to obtain the maximum values at the intersection points. The reduced one was used, modifying the multiplication factors in actions.

For fundamental combination, the equation described in Article 6.4.3.2 of Eurocode-0 shall be used accordingly:

$$\sum_{j\geq 1} \gamma_{G,j} G_{k,j} \text{"+"} \gamma_{Q,1} Q_{k,1} \text{"+"} \sum_{j>1} \gamma_{Q,i} \Psi_{0,i} Q_{k,i} \tag{1}$$

Where:

$\gamma_{G,j}$ = Partial coefficient relating to permanent action;
$G_{k,j}$ = Characteristic value of permanent action j;
γ_p = Partial coefficient for prestressing action;
P = Representative value of prestressing action;
$\gamma_{Q,1}$ = Partial coefficient for variable action 1;
$Q_{k,1}$ = Characteristic value of combined basic variable action 1;
$\gamma_{Q,i}$ = Partial coefficient relating to variable action 1;
$\Psi_{0,i}$ = Coefficient for determining the value of a variable action i;
$Q_{k,i}$ = Characteristic value of the accompanying action variable i.

Then, since the basic variable action is overload, we have:

$$1.0 * PP + 1.0 * RCP + 0.3 * SC \tag{2}$$

For combination with seismic actions, the equation described in Article 6.4.3.4 of Eurocode-0 shall be used accordingly:

$$\sum_{j\geq 1} G_{k,j} \text{"+"} P \text{"+"} A_{Ed} \text{"+"} \sum_{j>1} \Psi_{2,i} Q_{k,i} \tag{3}$$

Where:

$G_{k,j}$ = Characteristic value of permanent action j;

P = Representative value of a precompression action;

A_{Ed} = Design value of a seismic action; based on the importance factor, which in this case uses 1, in accordance with note 5 in section 4.2.5 of EC-8-1;

$\Psi_{2,i}$ = Coefficient for determining the value of a variable action i, which in this case is 0.3 in accordance with Table A.1.1 of Annex 1 to EC-0;

$Q_{k,i}$ = Characteristic value of the accompanying variable action i.

Therefore, due to the fact that the basic variable action is earthquake, there are 4 combinations, two for type 1 earthquake and two for type 2 earthquake, taking into account the two directions X and Y.

$$CombSismo1x = 1.0 * PP + 1.0 * RCP + 1.5 * Sismo1x + 0.3 * Sc \quad (4)$$

$$CombSismo1y = 1.0 * PP + 1.0 * RCP + 1.5 * Sismo1y + 0.3 * Sc \quad (5)$$

$$CombSismo2x = 1.0 * PP + 1.0 * RCP + 1.5 * Sismo2x + 0.3 * Sc \quad (6)$$

$$CombSismo2y = 1.0 * PP + 1.0 * RCP + 1.5 * Sismo2y + 0.3 * Sc \quad (7)$$

The combination of windings was used to obtain maximum and minimum values of forces at the intersection points. This combination is composed of all the combinations described in the previous topics, therefore:

$$\text{Wrap} = 1 * CombSismo1x + 1 * CombSismo1y + 1 * CombSismo2x + 1 * CombSismo2y + 1 * Comb\_\text{reduced} \quad (8)$$

3. DEFORMATION AND STRESS ANALYSIS

The first step in analyzing the appropriate structural reinforcement of a structure is to understand how it behaves when subjected to actions. Masonry buildings typically suffer greatly from earthquakes and exhibit structural anomalies in the first few days.

This chapter aims to analyze the building when seismic actions are applied to it. This topic will demonstrate which are the most critical regions that will serve as a basis for analyzing possible interventions in the following topics.

The basic values of the resistances have been provided and are broken down in the table below. For tension, 10% of the compressive strength value was taken into account.

Table. 4. Stress values used for analysis

Material type	longitudinal modulus of elasticity [MPa]	volumetric weight [kN/m^3]	compressive strength [kPa]	shear strength [kPa]
standard limestone masonry	690 ÷ 1050	19	600 ÷900	20 ÷ 32
solid ceramic brick masonry	1600 ÷ 3600	18	1900 ÷ 4200	60 ÷ 135

From the modal analysis, it was found that the fundamental mode in Y (mode 1) has a frequency value of 9.67 Hz and a mass participation of 75%. In X (mode 2), it has a frequency of 9.47 Hz and a mass participation of 76%.

In the "reduced" stress analysis all stresses come from the "reduced" combination for checking the model under vertical loads. All scales are in kPa, and the values were used so that the outer and inner walls could be analyzed together.

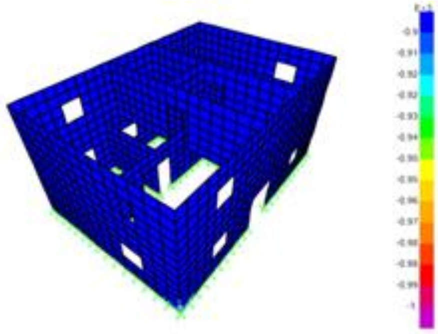

Fig. 2. Horizontal axial compression stresses

For horizontal axial tensile stresses, the exterior walls withstood the limits specified in the literature. However, small areas of the interior walls showed values above the limit (shown in dark blue), particularly in an area near an opening on the first floor, with values exceeding 200 kN/m^2.

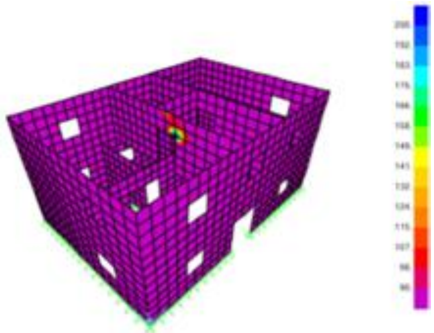

Fig. 3. Horizontal axial tensile stresses

For vertical axial compression stresses, all interior and exterior walls fall within the maximum limits.

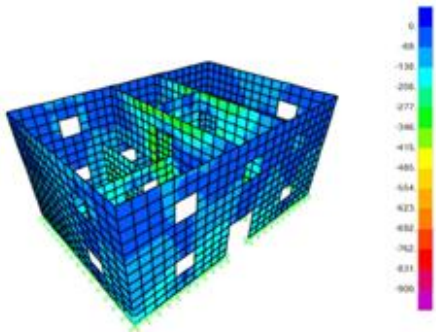

Fig. 4. Vertical axial compression stresses

For vertical axial tensile stresses, the outer walls, for the most part, withstood the limits specified in the literature. However, the inner walls showed values above the limit, especially in areas close to openings, with values exceeding 200 kN/m^2.

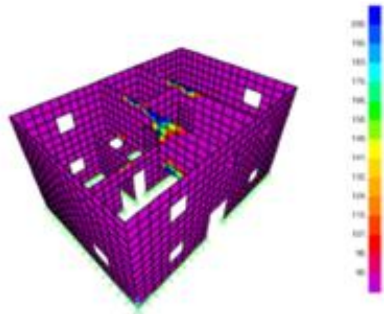

Fig. 5. Vertical axial tensile stresses

In terms of shear stresses, the exterior walls suffer little damage. However, some areas of the interior walls, in areas with openings, obtained values above the expected limit (dark blue areas).

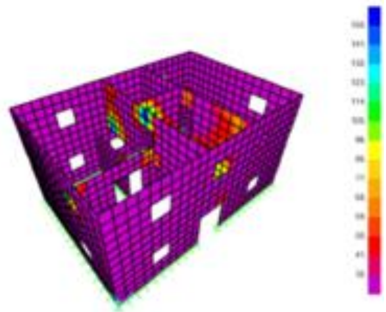

Fig. 6. Shear stresses

4. ANALYSIS OF "COVER" REQUESTS

All stresses listed below come from the "cladding" combination. All scales are in kPa, and we used values that made it possible to analyze the external and internal walls together.

For horizontal axial compression stresses, all interior and exterior walls are within the maximum limits.

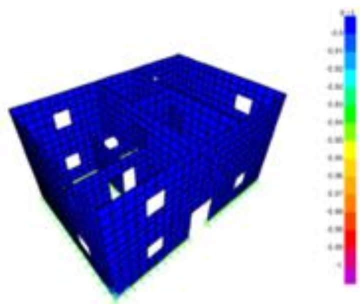

Fig. 7. Horizontal axial compression stresses

For horizontal tensile axial stresses, the exterior walls withstood the limits specified in the literature. However, small areas of the interior walls showed values above the limit (shown in dark blue), particularly in an area near an opening on the first floor, with values exceeding 200 kN/m^2.

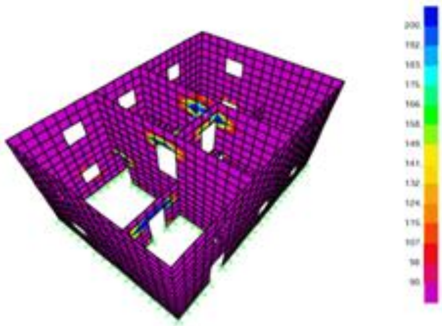

Fig. 8. Horizontal axial tensile stresses

For vertical axial compression stresses, all interior and exterior walls are within the maximum limits. This is confirmed by the fact that an earthquake is a horizontal force.

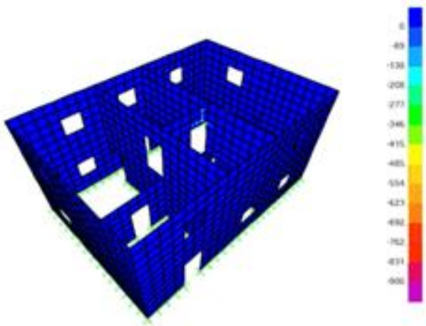

Fig. 9. Vertical axial compression stresses

For vertical axial tensile stresses, the exterior walls mostly withstood the limits specified in the literature. However, the interior walls showed values above the limit, especially in areas close to openings, with values exceeding 200 kN/m^2.

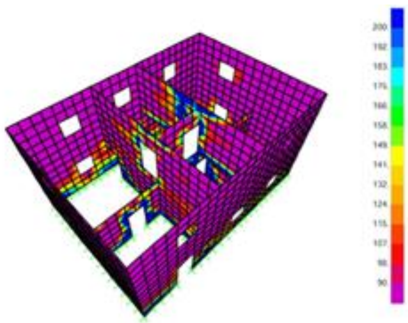

Fig. 10. Vertical axial tensile stresses

For shear stresses in the plane, in terms of shear stresses, the exterior walls suffer little. However, some areas of the interior walls, in the span zone, obtained values above the expected limit (dark blue areas).

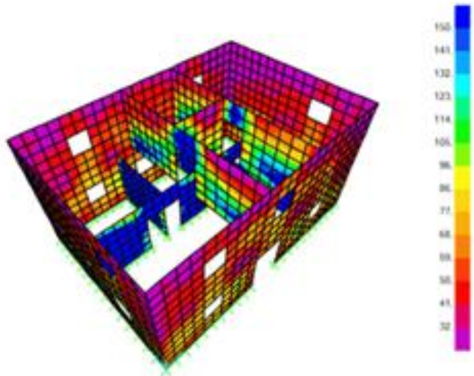

Fig. 11. Shear stresses

5. PROPOSALS FOR INTERVENTION

After analyzing the stresses, the following situations were verified:

- Occasional high horizontal tensile stresses in spans on internal walls on the ground floor and first floor;
- High horizontal tensile stresses in spans and on several internal walls;
- High shear stresses in the plane in almost all areas of the internal walls.

The proposed interventions were stipulated to consider the ICOMOS recommendations for the rehabilitation of historic buildings. The three fundamental principles were applied:

1. Principle of minimal intervention;
2. Principle of reversibility;
3. Principle of compatibility.

Table 5 below provides a brief summary of the situations identified, together with the respective areas and the proposed intervention.

Table. 5. Stress values used for analysis

Verified situation	Critical areas that need to be addressed	Proposed interventions
Horizontal and vertical tensile stresses (axial stresses)	Interior and exterior walls on the first floor and ground floor	Metal rods with clamps
	Openings on the first floor and ground floor	Reinforced plaster on both sides
	Exterior walls connected to the ground	Reinforced plaster on both sides
Shear stresses in the plane	Interior and exterior walls on the first floor and ground floor	Injections + synthetic mesh

The first proposed intervention involves the application of reinforced plaster for tension and shear reinforcement. The procedure includes removing deteriorated mortar and existing materials, cleaning the surface with a water jet, and applying a compatible repair material. A steel mesh is then installed, followed by the application of a new plaster layer to restore structural integrity. The plaster used has a thickness ranging from 3 to 5 centimeters, together with steel or polypropylene mesh that must be properly fixed to the masonry.

Since it is applied to both sides of the wall, the element must be connected by a metal confinement material protected against the risk of corrosion. After that, cement plaster is applied. This construction technique does not require formwork and allows it to be used in hard-to-reach places, always guaranteeing good adhesion and durability.

A considerable increase in the tensile strength of ordinary stone masonry walls from 90 to 225 kN/m^2 and from 32 kN/m^2 to approximately 80 kN/m^2 , taking into account a coefficient of increase in mechanical properties of 2.5. Considering also the good quality of the bedding material, an increase of 1.5 (50%) is expected for tensile and shear strength, i.e., an increase from 225 kN/m^2 to 337.5 kN/m^2 and from 80 kN/m^2 to 120 kN/m^2.

The second proposed intervention involves using metallic rods for tensile and shear reinforcement. The process includes drilling holes along the mortar joints through the wall section and inserting corrosion-protected metal anchors. This technique enhances the masonry’s mechanical performance by “stitching” the structure with adhesive bonding, improving its tensile and shear strength, and ensuring continuity in localized areas to increase overall stability.

The third proposed intervention combines masonry injection with a synthetic mesh to improve structural integrity. The process involves drilling holes and injecting a compatible cement-based mortar, preferably by gravity, to fill internal voids without causing further damage. A polypropylene mesh is then applied to strengthen the wall, enhancing its resistance to both shear and tensile forces.

As an alternative solution, an intervention imposed in EC08-1 in chapter 10, called "Base isolation," is suggested. This intervention is based on reducing the seismic response of the structure, which is achieved by increasing the fundamental period of the structure with seismic isolation, modifying the configuration of the fundamental vibration mode, and increasing damping. Since this intervention would require rebuilding the building's foundation to create a new configuration, these factors make such a solution less economically viable.

6. FINAL THOUGHTS

After considering the reinforcement methods, it was concluded that the interventions reduce the stresses in the building and, despite the fact that values above the permissible limits were found, it should be noted that the model has certain simplifications that justify such values, including:

• The model does not provide for openings at exact distances and dimensions, which would contribute to reducing axial stresses;

• The model is based on a simple linear analysis, while the ideal situation would be to use a nonlinear analysis with the help of calculation software such as TreMuri.

7. REFERENCES

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