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Features of the Masonry Structure Calculation with Vertical Ring Beams based on the European Standards

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Abstract. The design of masonry structures should remain a combination of traditional and modern knowledge. The Eurocodes in the field of the design of earthquake-resistant masonry structures, carry mostly acceptable and expected recommendations and requirements. This paper shows that they contain less acceptable principles, which require further experimental and analytical studies. Particularly it should be noted that Eurocode knows only a shearing mechanism by the horizontal coupling, although during the seismic load, the fracture usually occurs due to exceeding the main tensile stress, which manifests by opening diagonal cracks. The mechanism of the horizontal shearing by Eurocode is treated as critical for the seismic resistance of most masonry buildings, thus the masonry structure is attributed as sufficiently secure, although its actual seismic resistance would be far below from the required.

1 Introduction

The hazard of earthquakes in the Balkan region, situated in very complex geological and tectonic conditions, determine the relevance of this study (Fig. 1). Before the final adoption of European standards for the design of masonry structures on seismic areas, as much as they are considered advanced, it is necessary to perform detailed analysis and comparisons with our current regulations in order to obtain the synthesized experiences and accurate structural solutions, as well as eventually correcting and supplementing them [1-5]. In this regard, this paper analyzes classical three-story masonry structures with vertical ring beams applying valid (PZZ'81 and PIOVS'91) and European regulations (EC-6 and EC 8), for comparison of results.

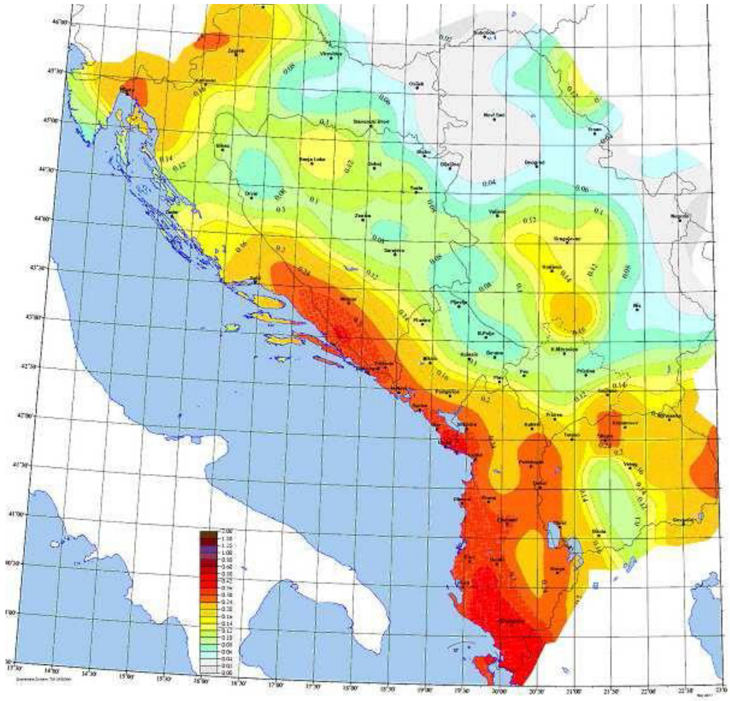

Figure 1. Seismic hazard maps, the Balkan region [7].

2 Materials and methods

We analyzed the masonry structure with vertical ring beams P+2S, floor height 2.8 m, with premises intend for household and housing. Supporting structure consists of walls of solid brick, 25 cm thick, built using a general-purpose mortar (Fig. 2).

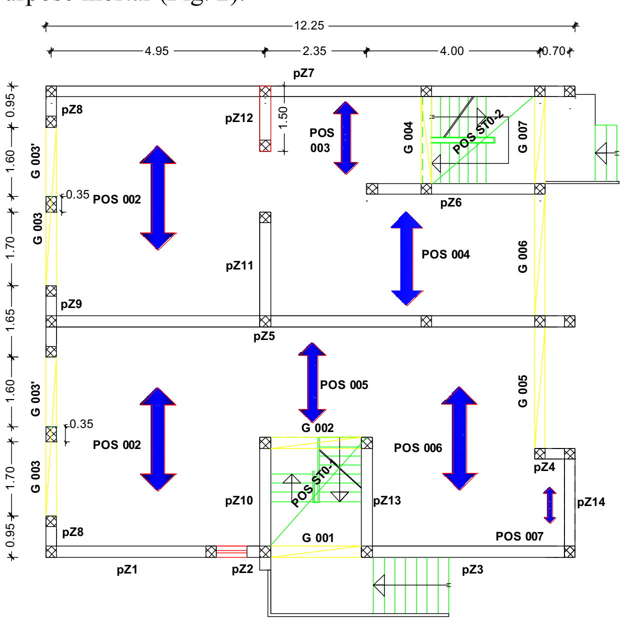

Figure 2. Ground floor basis [1].

Each wall is framed with vertical and horizontal reinforced concrete elements so they together act as a single structural element upon exposure of some influences [6]. When positioning horizontal and vertical ring beams, the requirements of EC 8 are adhered to, they are stricter than the applicable regulations. Ring beams are predicted at the level of each floor, on confrontment walls and on both sides of every orifice greater than 1.5m^2 (along with PZZ, the length of orifice is greater than 2.5 m). Additional ring beams are placed in the walls where the maximum spacing between the existing, both horizontally and vertically, was 4 m (5 m). Semi-prefabricated mezzanine structure type FERT, was applied [7-9].

The structure is positioned in the VIII zone of seismicity. The structure is founding on the type B of soil (according to Eurocode, which is equivalent to the category I by PZZ) [10, 11].

2.1 Determination of seismic load of elements

In the calculation we have considered the following loads acting on the structure: net weight of the structure, imposed load and seismic load. The intensity of the loads is determined in accordance with European regulations. The vertical load of the walls is determined using the area of influence [12, 13].

Since the majority of masonry structures has regularity in arrangement of the walls in the base and the height, it appears that the seismic response of the structure is not affected by the higher tones of oscillation, which allows the use of simple linear static method, the method of lateral force (MBS) [14]. The project's transverse seismic force on the ground floor of the structure, F_b, for each direction of action of horizontal forces is calculated as follows:

$$F_b = S_d(T_1) \cdot m \cdot \lambda \tag{1}$$

where:

Sd (T_1) - project spectrum ordinate. Since the masonry structures are rigid with their own period of oscillation, which is generally in the range where project spectrum of response is by Evrocode 8, horizontal line, Sd (T_1) can be determined by the expression (2);

m - total mass of the structure above the foundation or above the rigid basement area. The total mass includes permanent and temporary loads (temporary loads are multiplied by the corresponding coefficients given in the Eurocode 1, which take into account the purpose of the structure and the fact that the total weight of the imposed load is not present at the time of the earthquake in its full strength);

λ - the correction factor which takes into account that the effective modal mass of the building, with at least three levels and translational degrees of vibration in both orthogonal directions, less than the entire weight of the building.

The horizontal components of the seismic action by Eurocode 8:

$$S_d(T_1) = a_g \cdot S \cdot \eta \cdot \frac{2.5}{q} \tag{2}$$

where: a_g - design acceleration of the ground (a_g = 0.2g), S - factor of soil, η - correction factor of attenuation, q - structural behavior factor.

The elastic seismic forces reduction with the behavior factor of structure q (masonry structures with ring beams have the value from 2 to 3) is shown as a pretty good solution, by preventing the demolition of buildings and also the requirement about extent of damage retains an acceptable level [6]. The resulting value of the seismic force, F_b = 1139 kN, is proportionally divided into elements by their stiffness, where the accidental eccentricity of the mass during an earthquake, is considered, in two normal directions. Eccentricities obtained as recommended by Eurocode 8 (EC 8) and specific values obtained by subtracting the corresponding coordinates of the center of stiffness (C_k) and of the center of mass (C_m), are quite different, and hence the difference in the torque. The higher value is taken, the one obtained by EC 8, where the accidental eccentricity is estimated on 5% of the span length. Comparison of the seismic forces obtained by the applicable regulations (the method of equivalent static loads - PIOVS'91) and European regulations makes sense if it is about marginal influences. Specifically for this example, the European regulations obtained influences about 45% higher than those obtained by PIOVS. It is important to note that the safety factor with the effects of the seismic load by EC is γ = 1.0. The seismic force is reduced by a factor of behavior q = 2.0, in order to provide adequate ductility to the structure, it would not make sense to subsequently increase the impact. To ensure bearing capacity of the building, the impacts are increased by 50% with the current regulations [15-18].

2.2 Modeling of the structure

The structure is modeled in the software package SAP2000 v14 (Fig. 2). The amount of the seismic load transferred to the individual elements is calculated. The 'spatial line model' is used, where each floor is modeled separately because of the change in length of the walls of the individual floors. The walls of the ground floor are wedged on the bottom side, and prevented from rotation of both horizontal axes on top. All elements are connected by a diaphragm, which is rigid in its plane. The first floor is modeled in the same way, except the adequate axial and seismic load are added. And, the walls of the top floor are modeled to represent the associated console, et. from the top side like the other floors, elements are stiffened by the diaphragm. It should be noted that every wall is originally determined by the effective height and by the solid part, in order to take into consideration the fact that the seismic load does not activate the entire height of the wall.

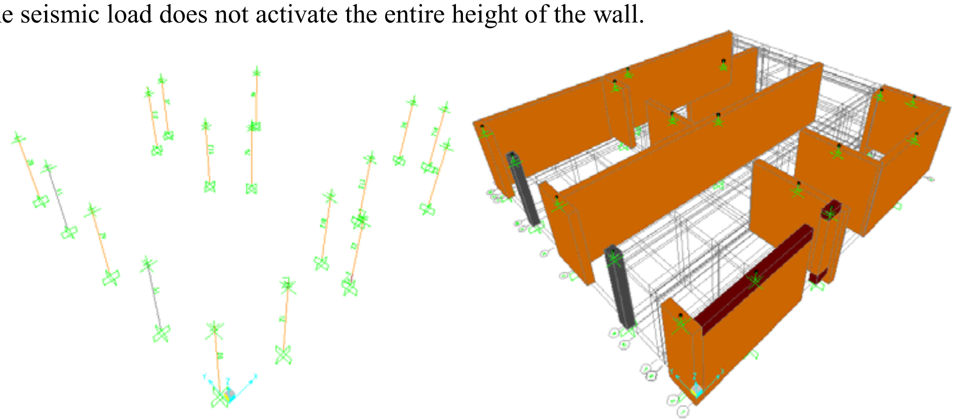

Figure 3. Spatial line model of the ground floor of the structure [1].

In modeling, special attention is given to proper allocation of material characteristics [19]. The values for the modulus of elasticity E = 3660 kN/m^2 and Poisson ratio υ = 0.3 are inputted in the model, so the obtained value of the shear modulus is equal to the G_{SAP} = 1407 MPa, while the actual modulus of brick shear, because of the anisotropy and heterogeneity of the material which is obtained experimentally is actually G_{real} = 400 MPa. Therefore, the modification of this modulus by the reduction coefficient has been made (Fig. 3):

$$0.5\frac{G_{real}}{G_{SAP}} = 0.1423 \tag{3}$$

where with this reduction coefficient of 0.5 is considered that during an earthquake the brick wall is going to enter the zone of plasticity.

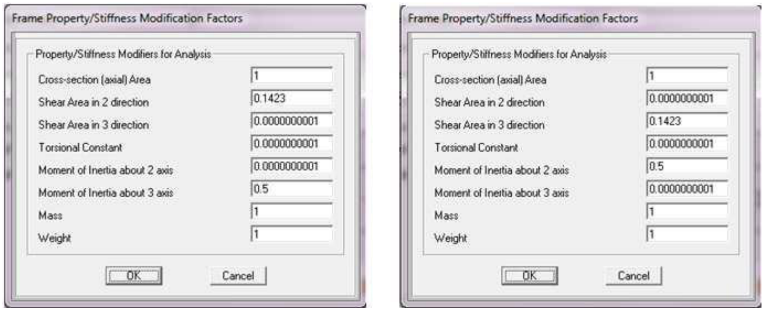

Figure 4. Material characteristics of the walls with the SAP2000 for the clay brick walls in the X and Y direction.

The period of oscillation obtained in SAP 2000 wasn't used as the relevant because of the nature of the model.

2.3 Dimensioning of the characteristic vertical structural element

Considering the geometry of the walls, their axial loads as well as horizontal, ie. seismic, the wall Z12 with critical direction is observed (Fig. 4). The conclusion was that this wall may be critical, due to its relatively low vertical load in relation to the horizontal, in terms of the resistance to the seismic loading.

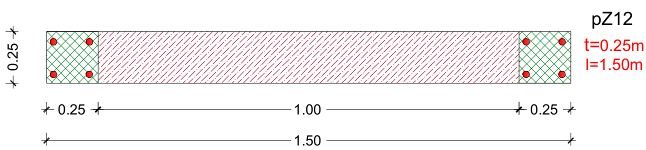

Figure 5. Dimensions of a typical wall at ground level.

The required material properties are determined in accordance with the provisions of Eurocode 6, except there wasn't basis to take the shear modulus, as previously noted, as well as the elastic materials, as recommended in this standard (40% of modulus of elasticity), because it's actual value in the best case reaches 10% of the modulus of elasticity [20-24].

2.4 Capacity of the wall exposed with predominantly vertical load

Bearing capacity of unreinforced walls in relation to the vertical load, must be based on the geometry of the wall, on the impact of present eccentricity and on the properties of used materials for building. In the calculation, the hypotheses of section flatness are valid, as well as the assumption that perpendicular tensile strength of the wall to the horizontal couplings is equal to zero [2]. Applicable and European standards consider the same influential factors when it comes to carrying capacity of the wall under pressure. It is believed that eccentricity is in the wall and is always at least 5% of its thickness. However, although the calculation principle is similar, the results are significantly different as can be seen in Tab. 1. With applicable regulations we are getting smaller capacity because the value of the buckling coefficient is less, and the value of the partial coefficient of the material is higher [25-27].

2.5 Capacity of the wall on shearing

Eurocode 6, which provides basic guidelines for the calculation of masonry structures, knows only the mechanism of sliding on a horizontal coupling (Fig. 5). This mechanism of the shear occurs if stresses on the pressure are low, so seismic forces can cause shearing of the upper part of the wall to the lowest on one of the horizontal couplings, in the long walls with poor quality of mortar. Sometimes walls behave like that in the upper part of buildings, under a rigid roof structure, where the accelerations are highest, and vertical loads are lowest [1].

To calculate the resistance of the wall on shearing, the boundary conditions as well as vertical and horizontal load acting on some walls, should be known. For the verification of the walls framed with the ring beams, capacity on the shearing (V_{Rd}) is taken as the sum of the capacity of the wall ($V_{Rd,z}$) and the concrete of the ring beams ($V_{Rd,c}$). Capacity on the shearing of the ring beam is obtained according to the rules in Eurocode 2, for the elements where is not necessary to calculate the reinforcement for the shearing:

$$V_{Rd} = V_{Rd,z} + V_{Rd,c} = f_{vd} \cdot t \cdot l_c \geq V_{Ed} \tag{4}$$

where: l_c is the length of the pressed part of the wall, neglecting any part of the wall that is exposed to tension, t the thickness of the wall, f_{vd} represents the value of the compressive strength of the wall on shearing, based on the average value of the vertical stresses of the pressed part of the wall that provides capacity on the shearing.

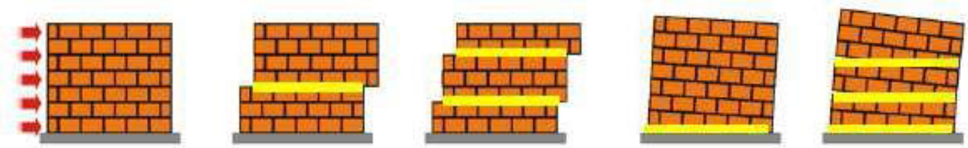

Figure 6. Mechanism of the shearing on horizontal coupling.

However, in a normal situation seismic forces cause the demolition of shearing, characterized by diagonal cracks (Fig. 6). It is, in fact, the mechanism of the destruction which in most cases determines the seismic resistance of masonry structures, and because of the cause of the cracks sometimes it is called demolition by diagonal tension.

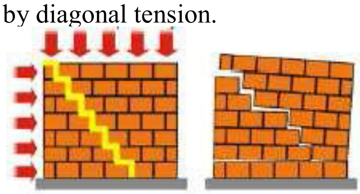

Figure 7. Mechanism of shearing with the appearance of diagonal cracks.

Applicable regulations, namely PIOVS'91, unlike European regulations, identified this mechanism of destruction ie. shearing of the wall, due to reaching the main tensile stresses. The average stress of the shearing in the wall element (τ_o), from the seismic action which the element is receiving, per unit length of the wall, is obtained by the formula:

$$\tau_0 = \frac{\sigma_{0,rus}}{1.5} \sqrt{1 + \frac{\sigma_0}{\sigma_{0,rus}}} \tag{5}$$

where:

σ_o - average stress in the wall element of the vertical load;

$\sigma_{o,rus}$ - major tightening stress in the wall element at the moment of demolition, for certain types of walls.

Regarding the calculation of the capacity of an unreinforced wall, Turncek and Cacovic proposed an equivalent equation to (5), except that factor b may vary from 1.5 to 1.1, but the equation above uses the constant value (1.5). The geometry of the wall and the actual ratio of vertical and horizontal load during demolition, on distribution of the shearing stress over the wall, are taken into account with this factor [28 – 30].

2.6 Capacity of the walls exposed to bending and / or axial load

In practice, when the wall is loaded by wind or earthquake mostly expressed stresses are shearing. Damages of the load-bearing walls that arise solely due to bending are rare [31].

In the section of control of the capacity on bending in its own plane, PZZ remained incomplete, while PIOVS'81 regulations don't mention this load [32-33].

By European standards, during the verification of the walls framed with the ring beams that are exposed to bending and / or axial load, valid assumptions for reinforced masonry elements, given in the EC 6, are approved. The highest calculated moment of bending the wall (M_{Rd}), loaded in its plane, with the neglected impact of press fitting of the ring beams, is equal to:

$$M_{Rd} = \frac{\sigma_d \cdot t \cdot l^2}{2} \cdot \left(1 - \frac{\sigma_d}{f_d}\right) + A_{rv} \cdot f_{yd} \cdot \frac{1-d}{2} \tag{6}$$

where: σ_d - average compressive stress in the wall of the vertical load; f_d - calculated value of the compressive strength of the wall; f_{yd} - calculated value of the strength of reinforcing steel; l, t, d - the dimensions of the wall; A_{rv} - surface of ring beam reinforcement.

3 Results and discussion

Discussed wall of thickness t = 25 cm, Z12, loaded with a normal force of constant load N_g =70.3 kN and with a horizontal force due to seismic impacts F_d = 83.8 kN, did not satisfy the stress control on the shearing, as well as the control of the main tensile stresses, an iterative procedure determined an adequate wall thickness (Tab. 1).

The wall with a thickness of 64 cm, according to the calculation, is sufficient, and satisfies the main control of tensile stress. However, the shear capacity is only satisfied with a wall thickness of 125 cm, leading to the formulas given in PZZ, or 86 cm, by European regulations. Approval of the wall of that thicknesses is absurd, because in practice, the fracture due to only shearing, is very rare [1].

Table 1. Values of the capacity of the wall Z12 on the pressure (N_{gr} / N_{Rd}), shearing (T_{gr} / V_{Rd}, bending (M_{gr} / M_{Rd}) and tension ($T_{gr,z}$ / $V_{Rd,diag}$)

	Applicable regulations				European standards			
T[cm]	N_{gr} [kN]	T_{gr} [kN]	M_{gr} [kN]	$T_{gr,z}$ [kN]	N_{Rd} [kN]	V_{Rd} [kN]	M_{Rd} [kNm]	$V_{Rd,diag}$* [kN]
25	228.8	125.7	254.9	64.3	658.8	35,0	214.8	42.4
38	347.7	47.4	283.4	88.7	974.4	45.4	216.8	56.8
51	466.7	60.4	310.9	112.8	1331.3	55.8	217.5	70.6
64	585.6	73.4	323.3	136.6	1688.1	66.2	218.1	84.2
Note*: Taken from the Slovenian regulations								

4 Summary

It is undisputed that the design of masonry structures should remain a combination of traditional and modern knowledge. Analysis of masonry constructions is done simultaneously by applying the Rules on technical standards for masonry walls (PZZ'81), Regulation on technical standards for the

constructions in seismic areas (PIOVS'91) and Eurocodes (EC 6 and EC 8). Eurocode presupposes shear force to be a reliable mechanism form calculating shear wall resistance force, which conflicts to the real behavior of constructions during earthquakes. It is therefore recommended determining the seismic masonry resistance according to the current rules that require verification tensile strain, whose possible exceeding leads to the appearance diagonal wall cracks.
The Eurocodes in the field of the design of earthquake-resistant masonry structures, carry mostly acceptable and expected recommendations and requirements. However, the paper shows that they contain less acceptable principles, which require further experimental and analytical studies. Particularly it should be noted that Eurocode knows only a shearing mechanism by the horizontal coupling, although during the seismic load, the fracture usually occurs due to exceeding the main tensile stress, which manifests by opening diagonal cracks. So the mechanism of the horizontal shearing by Eurocode is treated as critical for the seismic resistance of most masonry buildings, thus the masonry structure is attributed as sufficiently secure, although its actual seismic resistance would be far below from the required.

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