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Lateral Strength-Based Seismic Evaluation of an Unreinforced Masonry Building

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Abstract

Unreinforced concrete masonry (URM) buildings located in seismic areas still constitute an important portion of the residential building stock of Turkey. A significant amount of these buildings is designed according to allowable stress criteria of the 2007 version of Turkish Earthquake Code. However, seismic design philosophy, as well as seismic performance assessment, of URM buildings tends to focus on the lateral strength of URM walls and it is also adopted to the current version of Turkish Earthquake Code. Accordingly, the seismic performance of a URM building designed based on the theory of allowable stress is a significant concern. In this study, the seismic performance of a two-story URM building is investigated based on the ultimate strength method. The case study building is primarily designed in accordance with seismic requirements of the 2007 version of Turkish Earthquake Code. Subsequently, lateral strength-based seismic performance assessment of the same building is performed. The earthquake demand is represented by a 5%-damped elastic acceleration design spectrum and the lateral strengths of URM walls are calculated in accordance with provisions of the current Turkish Earthquake Code. All analyses are conducted on a very detailed three-dimensional finite element model (FEM) of the building. The results have shown that the lateral strength capacities of some URM walls located on the ground floor are exceeded, whereas none of the URM walls on the upper floor reach their capacities. As a result, collapse prevention performance level is not achieved.

Key words

URM building, Seismic evaluation, FEM, Allowable stress, Lateral strength

1. INTRODUCTION

Seismic hazards posed by existing URM buildings have long been recognized and reported after past earthquakes occurred in active seismic zones in the world, as well as in Turkey. URM buildings are likely to suffer extensive damage and could partially or completely collapse during major seismic events. Since mechanical properties of masonry components are more complicated than their modern counterparts and due to several other reasons such as workmanship employed in masonry construction, poor construction quality, lack of maintenance, an adequate prediction of the seismic behavior of URM buildings is one of the fundamental topics in earthquake engineering. Although URM is one of the oldest building construction techniques, the seismic behavior of those types of buildings is still one of the least understood.

Typical URM buildings in Turkey have brick walls with no steel reinforcing bars embedded within them. They are commonly located in rural regions to be used for residential purposes. Some of these buildings have

structural deficiencies due to inappropriate seismic design whereas the others are constructed ignoring the code requirements. Moreover, before the 2007 version of Turkish Earthquake Code (TEC) [1], earthquake analysis of URM buildings is not imposed when both masonry material and geometric requirements of the code are satisfied. The most significant improvement in the seismic design of masonry structures in Turkey is the addition of simple procedures for the calculation of vertical compression and shear stresses developed in masonry walls subjected to earthquake loading. When the current version of the code, Turkey Building Earthquake Code (TBEC) [2], was published, the seismic design of URM buildings is refined from allowable stress theory to ultimate strength philosophy. It is quite clear that URM buildings designed in accordance with the stress-based code requirements are expected to satisfy the lateral strength-based criteria of TBEC.

Several studies have been conducted on seismic behavior and design of URM buildings. Some of these studies have been focused on developing reliable modeling techniques for seismic analysis and risk assessment of URM buildings [3]–[10]. Earthquake analysis [11]–[14], as well as seismic performance and risk assessment [15]–[24], of URM buildings, have been widely studied. Since URM buildings are characterized by a high seismic vulnerability, seismic retrofitting of these buildings always remains relevant [25]–[29]. On the other hand, construction of URM buildings continues, and accordingly, seismic design procedures and code regulations regarding URM construction are current topics of high importance [30]–[33].

The main purpose of the present paper is to perform a lateral strength-based seismic evaluation of a URM building seismically designed based on the theory of allowable stress. Regularization of a real URM building's geometry is firstly performed. Then, a 3D FEM model of the URM building is created in SAP2000 platform and geometrical and seismic considerations of TEC are used to achieve the design. Finally, lateral strength-based seismic evaluation of the URM building is performed in accordance with TBEC. Thereby, it is investigated to what extent the seismic performance objectives of TBEC are satisfied by a typical residential URM building.

2. CONSIDERED URM BUILDING: CHARACTERISTICS AND SEISMIC DESIGN

2.1. Material Properties and Geometric Considerations

An architectural design of a two-story residential URM building with a story height of 2.7 m is achieved. Thicknesses of load-bearing masonry walls are taken to be 200 mm, which is the minimum value imposed by Turkish Earthquake Code [1]. The walls are composed of clay brick units with dimensions of 190 mm $\times$ 290 mm $\times$ 135 mm and a weight per unit of volume of 7 kN/m³. Reinforced concrete (RC) slab of 100 mm thickness is used. A bond beam with a height of 200 mm is integrated on each load-bearing masonry wall. The uniaxial compressive strength of concrete used in slabs and bond beams is 25 MPa. The plan view of the URM building with a total area of 95.39 m² is shown in Figure 1.

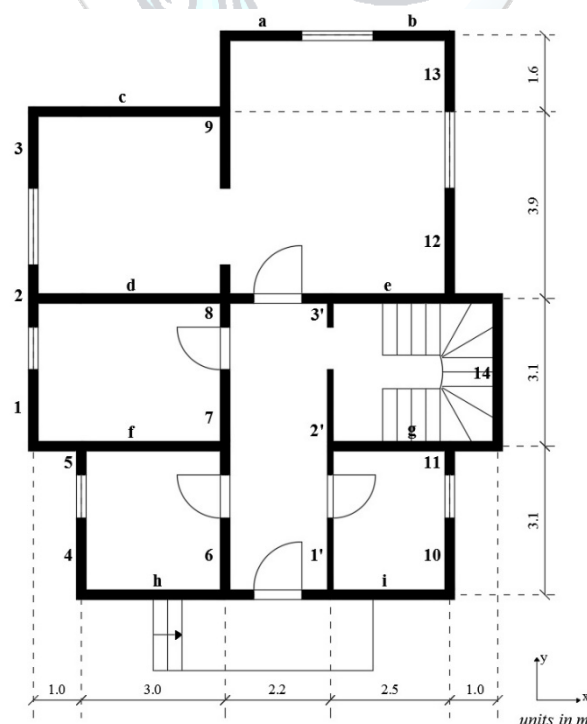


Figure 1. Plan view of URM building

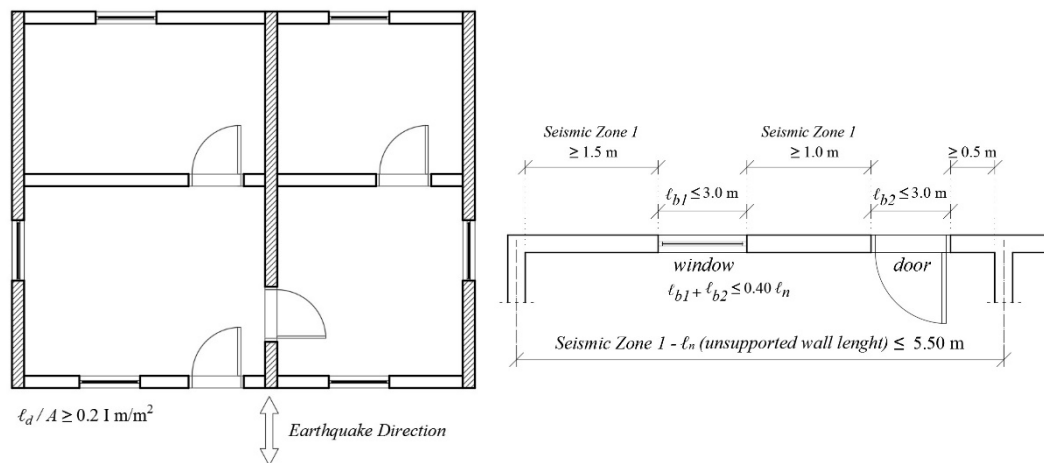


Figure 2. a) Solid wall lengths

b) Unsupported wall lengths and openings

Geometrical considerations of Turkish Earthquake Code are used to achieve the design. The ratio of the total length of load-bearing walls (l_d) to the floor area is computed to be 0.32 m/m^2 in x-direction and 0.25 m/m^2 in y-direction. This ratio shall not be less than $0.2I \text{ m/m}^2$ in two orthogonal directions. The building importance factor (I) depending on type of occupancy is 1 (i.e., $I = 1$). The unsupported length of load-bearing wall between the axes of load-bearing walls in the direction perpendicular to itself is taken to be 5.5 m, which is the maximum value that can be considered for URM buildings located in seismic zone 1. The length of the solid wall parts at the corners of the building is employed to be greater than 1.5 m. In addition, this value is taken at least 0.5 m for interior walls. The length of solid walls between door and window openings, which cannot exceed 3 m and 40% of the wall length, is considered to be at least 1 m. All geometrical design criteria taken into consideration for the design of URM building are summarized in Figure 2.

2.2. Seismic Design

A very detailed three-dimensional FEM model of the building is created in SAP2000 platform [34]. A modeling technique of plane finite elements is implemented to simulate masonry brick walls. Accordingly, brick masonry walls are discretized with square finite elements of $100 \text{ mm} \times 10 \text{ mm}$. Masonry elastic modulus is related to masonry compressive strength (i.e., $f_{me} = 3.5 \text{ MPa}$), and taken to be $E_{me} = 2625 \text{ MPa}$, whereas the expected shear modulus of masonry is employed as 0.4 times the elastic modulus. The 3D finite element model of the building is shown in Figure 3.

Having completed the analytical model, the free vibration properties of the URM building are calculated as a result of an eigenvalue analysis conducted in SAP2000 platform. Seismic masses are calculated as the combination of dead loads (i.e., elements self-weight), and 30% of live loads, which are assumed uniformly distributed on floors and taken equal to 2 kN/m^2 . Accordingly, the total seismic mass is computed to be 118.84 tons. Elastic fundamental period of vibration of the URM building is obtained to be 0.064 and 0.058 s in x- and y- directions, respectively. It is quite clear that the URM building has short vibration periods, which means that it receives elastic spectral forces specified in the acceleration amplification region of the design spectrum.

The studied URM building is designed according to 5% damped horizontal elastic acceleration response spectrum of the 2007 version of Turkish Earthquake Code representing the design basis ground motion with a reference exceedance probability of 10% in 50 years. The peak ground acceleration is $0.4g$, where g is the gravitational acceleration. The considered URM building is of ordinary importance and it is assumed to be on soil with an average shear-wave velocity in the upper 30 m of the soil profile of $360 < V_{s30} \leq 760 \text{ m/s}$. A response reduction factor of 2 (i.e., $R_d(T_1) = 2$) is employed to account for the reduced design spectrum.

Shear stresses developed in masonry walls subjected to design basis earthquake loading are computed as a result of finite element analyses conducted in SAP2000 platform. The seismic design of the considered URM building is achieved by satisfying the allowable shear stress criteria of Turkish Earthquake Code given in Eq. (1):

$$\tau \leq \tau_0 + \mu \cdot \sigma \quad (1)$$

where τ is the computed shear stress in a masonry wall, τ_0 is the allowable cracking stress of a masonry wall, μ is the coefficient of friction which can be taken as 0.5 according to Turkish Earthquake Code, and σ is the vertical compression stress developed in a masonry wall. The allowable cracking stress of a masonry wall is taken to be 0.25 MPa .

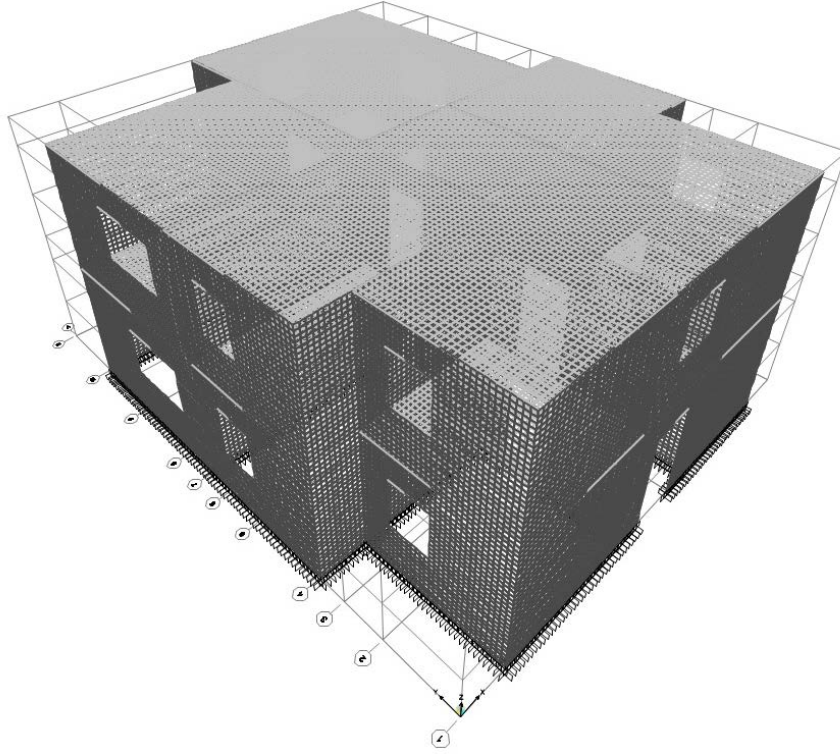


Figure 3. Finite element model of URM building

Considering the vertical compression stress developed in masonry walls, the allowable shear stress is computed as 0.35 MPa. The maximum shear stresses in the first story are obtained to be smaller than 0.35 MPa in x- and y-directions.

3. LATERAL STRENGTH-BASED SEISMIC EVALUATION

Lateral strength-based seismic evaluation of URM building is performed in accordance with TBEC [2]. The total design base shear forces in two orthogonal horizontal directions are computed from the elastic acceleration response spectrum of TBEC. The peak ground acceleration (PGA) of the considered earthquake is 0.708 g, where g is the gravitational acceleration, and the peak ground velocity (PGV) is 56.19 cm/s. The mapped short-period spectral response acceleration parameter (S_s) and the mapped spectral response acceleration parameter at a period of 1 s (S_1) are 1.735 and 0.469, respectively. Accordingly, spectral response acceleration parameters at short period (S_{DS}) and 1 s period (S_{D1}) are calculated to be 2.082 and 0.704, respectively. Corner periods for the employed horizontal elastic acceleration design spectrum are computed as $T_A = 0.068$ s and $T_B = 0.338$ s.

The vertical earthquake load effect is approximated by

$$E_v = (2/3)S_{DS} \cdot G \quad (2)$$

where S_{DS} is the design spectral response acceleration parameter at short period and G is the effect of dead load. The URM building is analyzed under combined earthquake and gravity loads using several combinations of factored loads and the resultant design shear forces are obtained.

The seismic performance evaluation of URM buildings according to TBEC is based on a comparison of lateral shear force capacity (V_{Rd}) of load-bearing walls with corresponding design shear force (V_{Ed}) in two orthogonal directions. The lateral shear force capacity of a load-bearing wall is considered the smallest value obtained from Eq. (3):

$$V_{Rd} = 0.5f_{vk} \cdot t \cdot l_c \quad (3a)$$

$$V_{Rd} = l \cdot t \cdot \frac{0.75f_{vko}}{b} \sqrt{1 + \frac{N_{Ed}}{0.75l \cdot t \cdot f_{vko}}} \quad (3b)$$

where t is the wall thickness, l_c is the wall-length in compression, l is the wall length, b is the ratio of wall height to wall length and shall not be taken less than 1 and greater than 1.5 for use in Eq. (3b), f_{vko} is the initial characteristic shear strength of masonry wall, and N_{ed} is the design vertical force. The characteristic shear

strength of masonry walls (f_{vk}) can be obtained through Eq. (4) considering the average vertical compression stress (σ_d) and shall not exceed 10% of masonry unit compressive strength (f_b):

$$f_{vk} = f_{vko} + 0.4\sigma_d \leq 0.10f_b \quad (4)$$

4. RESULTS AND DISCUSSION

Maximum shear forces developed in load-bearing masonry walls, as well as the corresponding lateral shear strength of load-bearing masonry walls, are listed in Table 1, where wall IDs of lower case letters and numbers stand for load-bearing masonry walls oriented in x - and y -directions has shown in Figure 1. It can be seen from the data in Table 1 that the shear force capacities of three masonry walls (wall ID c, d, and e) oriented in x -direction on the first floor are exceeded. Moreover, the shear force capacities of three masonry walls (wall ID 7, 9, and 14) oriented in y -direction on the first floor are also exceeded. However, design earthquake-induced shear forces acting on second-floor masonry walls are computed to be smaller than the shear force capacities of the corresponding walls.

Load-bearing masonry walls of which shear force capacities are exceeded are shown in orange in Figure 4. Relatively high shear forces are developed in these masonry walls due to their excessive rigidities. The contribution of these masonry walls to story shear force is computed to be 49.27% and 41.64%, respectively in x - and y - directions. These ratios are greater than 40%, the limiting value of TBEC. It is apparent from this result that the considered URM building does not satisfy the collapse prevention performance objective of TBEC.

On the other hand, shear force demands imposed on masonry walls “d” and “e” are slightly greater than their capacities (i.e., the demand/capacity ratio of these walls is 1.009 and 1.026, respectively). The same finding is observed for wall “7”, where the shear force demand/capacity ratio is computed to be 1.029. It is quite clear that both earthquake demand and capacity of a masonry wall are inherently probabilistic concepts. If the demand/capacity ratio of the aforementioned masonry walls were slightly below 1, the same building would satisfy the damage control performance level of TBEC.

Table 1. Comparison of shear force demands with capacity related limits

		Developed shear forces (kN)		Shear force capacities (kN)	
	Wall ID	1st floor	2nd floor	1st floor	2nd floor
x- direction	a	40.08	24.92	56	53.77
	b	38.65	19.88	56	54.59
	c	161.63	118.16	140	140
	d	162.46	121.55	161	161
	e	146.66	118.20	143	143.5
	f	120.60	86.85	140	140
	g	98.40	67.37	122.5	122.5
	h	101.57	69.28	126	126
	i	85.44	53.65	108.5	108.5
y- direction	1	46.36	28.15	56.00	55.02
	2	25.31	13.16	45.50	43.55
	3	41.62	19.43	56.00	56.00
	4	43.53	23.24	56.00	55.20
	5	11.21	11.62	20.69	18.98
	6	46.10	32.80	56.00	56.00
	7	79.22	49.49	77.00	77.00
	8	32.08	29.85	45.50	39.76
	9	137.45	84.46	112.00	112.00
	1'	25.02	18.73	51.12	48.28
	2'	38.86	24.87	77.00	77.00
	3'	5.60	8.82	21.00	20.23
	10	42.90	24.52	56.00	55.75
	11	11.29	12.69	20.56	18.58
	12	80.18	54.11	80.50	80.50
13	44.05	19.68	56.00	54.33	
14	135.92	106.73	108.50	108.50	

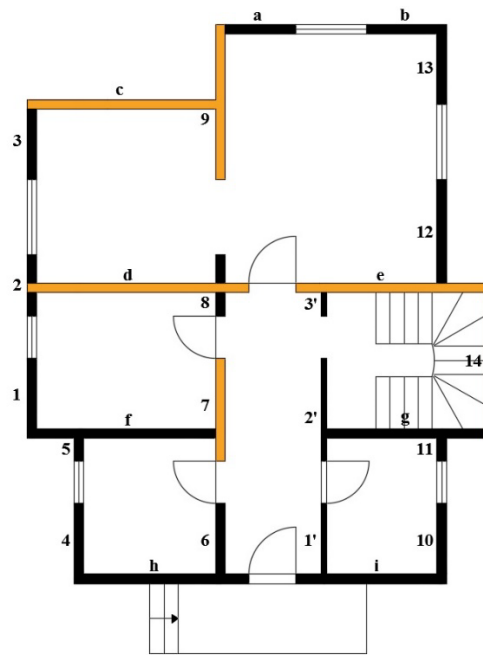


Figure 4. Damaged masonry walls (in orange)

5. SUMMARY AND CONCLUSIONS

The seismic performance of a three-dimensional URM building which is seismically based on the theory of allowable stress is evaluated comprehensively by considering the lateral strength-based criteria of TBEC. The analyses are conducted based on the finite element model of the building. The following conclusions can be drawn from the presented study:

- Although the considered URM building is seismically designed according to allowable stress criteria of the 2007 version of Turkish Earthquake Code, it does not satisfy the collapse prevention performance objective of TBEC.
- Remarkable high shear forces are developed in long masonry walls. These walls cannot sustain the high shear forces due to their relatively low capacities of shear force.
- First-story load-bearing masonry walls are found to be more vulnerable to earthquake loading.
- Both seismic demand and capacity are probabilistic concepts. Accordingly, it is quite questionable to assign deterministic values limiting seismic performance levels without considering the scattering, as implemented in TBEC.

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