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Wall index requirements for seismic design and assessment of masonry buildings

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Abstract

Wall Index (WI), also known as “wall density”, is a ratio of the total cross-sectional area for all structural walls aligned in one direction of the building’s floor plan and the gross floor plan area. Reconnaissance studies after past earthquakes in countries like Chile, Mexico, and China, confirmed that WI is one of the key parameters related to seismic performance of loadbearing masonry structures which influences the extent of earthquake damage. The WI requirements have been included in several international codes and guidelines. According to Eurocode 8 (EN 1998:1-2005), WI can be used as a design parameter for seismic design of simple masonry buildings with regular configuration and limited height up to 5 storeys, as an alternative to a more elaborate and complex seismic analyses approaches. The required WI for a building depends on the seismic hazard for the building site, number of storeys, type of masonry (unreinforced/reinforced/confined) and the mechanical properties of masonry (compressive/shear strength). WI can be also used for seismic assessment of existing masonry buildings in pre- and post-earthquake situations, as documented by studies from Chile and Mexico. The paper will provide a comparison of the masonry design requirements from selected codes, including the 1964 and 1981 Yugoslav technical regulations for design and construction of buildings in seismic regions and Eurocode 8. A case study of a masonry residential building which was damaged in the 2010 Kraljevo earthquake (M 5.5) and evaluated using different codes is also presented in the paper.

Key words: masonry buildings, seismic design, earthquake damage, wall density, wall index, Eurocode 8, Serbia

1 Background

Masonry is a traditional construction technology which has been used for housing construction in many European countries, including Serbia. Ancient masonry structures were usually constructed using stone masonry, but since the second half of 19th century clay bricks have been used for construction of residential and public buildings. Although reinforced concrete (RC) has emerged as a technology of choice for construction of mid-rise and high-rise buildings, including residential buildings, masonry remained prevalent construction technology for low-rise single-family housing and also smaller mid-rise apartment buildings in Serbia and other European countries located in the moderate to high seismic hazard areas. Serbia is located in a region of moderate seismic activity, however its territory is close to regions of high seismic hazard which triggered major earthquakes in recent history, e.g. the 1979 Montenegro earthquake (M 6.9), the 1977 Vrancea, Romania earthquake (M 7.2), and most recently the 2020 Petrinja, Croatia earthquake (M 6.4). In the last 100 years more than 10 earthquakes with magnitude 5.0 or higher occurred in Serbia. The most significant earthquake in the 20th century occurred in 1922, had magnitude 6.0 and epicentre near Lazarevac (approximately 60 km aerial distance from the capital Belgrade).

According to the 2011 Census of Serbia data [1], low-rise single family buildings constitute 95 % of the national residential building stock, corresponding to 65.9 % housing units. Multi-family housing accounts for only 2.6 % of the housing stock in terms of the number of buildings, but the proportion is significantly higher (33 %) in terms of the number of housing units [2]. Although official information is not available it is expected that large majority of single-family buildings were constructed using masonry technology, and also a large portion of the multi-family residential buildings, particularly in the period from 1945-1990, when Serbia was a part of the SFRY (former Yugoslavia). It is estimated that 72 % of all residential buildings in Serbia were constructed between 1946 and 1990. Majority of multi-family residential buildings from the pre-1963 vintage, mostly 3 to 5 storeys high, were constructed as URM buildings. After the first national seismic design code was issued in 1964 the construction of multi-family masonry housing continued at a smaller scale. Period from 1964-1980 was characterized by a construction boom. Reinforced concrete (RC) technology was widely used both for prefabricated and cast-in-situ housing construction. Loadbearing masonry continued to be a prevalent system for construction of low-rise buildings. Masonry walls in buildings located in high seismic zones (VIII and IX) had to be reinforced with horizontal and vertical RC confining elements (confined masonry). In the 1960s solid clay bricks were slowly replaced by modular masonry blocks. It is expected that masonry structures account for a significant fraction of the housing stock in other countries which were a part of the former Yugoslavia.

Seismic vulnerability of unreinforced masonry buildings (URM) has been confirmed by numerous earthquakes around the globe. These buildings are heavy due to relatively thick and massive masonry walls, and are robust and rigid. As a result, spectral accelerations and the corresponding earthquake-induced inertial forces are higher than those in light-weight buildings of similar size, e.g. timber buildings. URM structures are particularly vulnerable to earthquake effects due to limited masonry tensile strength. Seismic behaviour of URM walls can be characterized as brittle, since cracks develop when the tensile stresses exceed the masonry tensile strength; this is frequently the case in URM buildings located in epicentral regions of moderate earthquakes with magnitudes in the range of 5.0 and higher. Although these URM structures may exhibit nonlinear behaviour in the post-cracking stage, their ductility is limited and the overall performance is inferior when compared to otherwise similar RC and steel structures. Although Serbia was not exposed to major earthquakes since 1945, the 2010 Kraljevo earthquake (M 5.4) confirmed vulnerability of URM buildings [3].

This paper presents an overview of past and present code provisions related to seismic design of masonry buildings, with a special focus on multi-storey URM buildings typical for Serbian urban centres. Besides the past seismic design codes which were followed in the design of existing masonry buildings in Serbia, provisions of Eurocode 8 pertaining to seismic design of masonry buildings have also been discussed, with the focus on rules for simple masonry buildings. Finally, a case study of a multi-family URM building damaged in the 2010 Kraljevo earthquake presented.

2 Historic overview of seismic design provisions for masonry buildings

The first comprehensive seismic design code in the SFRY was published in 1964 [4] and was prompted by the 1963 Skopje earthquake. Subsequent version of the code was issued in 1981 [5] and it was the governing design code in Serbia until 2019, when Eurocodes were officially adopted as governing codes for the design of building structures in the country [6]. In particular, Eurocode 8 – Part 1 [7] has been adopted for seismic design of new structures in Serbia (SRPS EN 1998-1/NA:2018) [8]. Masonry buildings addressed by seismic design codes in Serbia can be classfied as ordinary (unreinforced) masonry, confined masonry, and reinforced masonry. Ordinary masonry buildings have horizontal RC confining elements at floor levels, which are often called seismic belts or ring beams. These elements are integrated with floor/roof slabs. Confined masonry buildings have horizontal and vertical RC confining elements, hence the main difference between ordinary and confined masonry buildings is the provision of vertical confining elements. Finally, reinforced masonry buildings have horizontal reinforcement placed in mortar bed joints, in addition to horizontal and vertical confining elements. Table 1 presents a summary of building height restrictions applicable to ordinary (OM) and confined masonry (CM) buildings.

Design of masonry structures has been governed by applicable codes, starting with the 1949 design code for masonry walls [9] to the latest code in former Yugoslavia issued in 1991 [10, 11]. Eurocode 6 (EN1996-1-1:2004) [12] has been recently adopted as official code for the design of masonry structures in Serbia [13]. A comparison of provisions related to seismic design of ordinary masonry buildings from various codes is presented in Table 2.

Table 1. Height limits (max number of storeys) for ordinary masonry (OM) and confined masonry (CM) buildings prescribed by the codes in Serbia from 1945-present

Seismic intensity (MCS)	PTP-12 [4] (1964-1980) OM | CM	PTN-S [5] (1981-2019) OM | CM	EN 1998-1:2005 [7]* (2020-present) OM | CM
VII	5 6	3 5	3 4
VIII	4 6	2 4	2 3
IX	3 5	n/a 3	n/a 2
Notes: * - simple masonry buildings according to Cl 9.7; n/a - not acceptable			

Table 2. Overview of seismic design provisions for ordinary masonry buildings in Serbia from 1964-present

Provision	PTP-12 [4] (1964-1980)	PTN-S [5] (1981-2019)	PTN-Z [10] (1991-2019)	EN 1998-1:2005 [7, 8] (2020-present)
Materials	Cement:lime:sand mortar mandatory, except single-storey bldgs in zones VII and VIII	Cement:lime:sand mortar mandatory; grade M25-M50 (2.5-5.0 MPa)	Cement:lime:sand mortar grade M2 (2.0 MPa) or cement mortar grade M10 (10.0 MPa)	Min mortar compressive strength 5.0 MPa
		Masonry units with horizontal holes not permitted	Solid clay bricks, modular clay blocks permitted	Detailed classification of masonry units
		Min strength for solid clay bricks MO100-MO150 (10-15 MPa); modular clay blocks MO150 (15 MPa)	Min strength for solid clay bricks and modular clay blocks 10 MPa	Min unit compressive strength 5.0 MPa
Walls-Thickness	25-38 cm	min 19 cm	min 24 cm (exterior walls) and 19 cm (interior walls)	min 24 cm
Floor/roof diaphragms	Rigid diaphragms required	Rigid diaphragms required		Rigid diaphragms required
Design method	Allowable Stress Design	Allowable Stress Design; Ultimate Limit States Design (strength only).	Allowable Stress Design; Ultimate Limit States Design (strength only)	Ultimate Limit States Design (strength plus serviceability)

According to Section 9.6 of Eurocode 8, Part 1 [7], seismic design of masonry buildings can be performed by one of the following approaches: a) a prescriptive approach called "Rules for simple buildings", which is applicable to regular low-rise buildings and different seismic hazard levels (Section 9.7 of Eurocode 8, Part 1), or b) an engineered analysis and design approach, which requires verification of safety against collapse to be performed for each structural element in a building, while the design resistance is determined according to Eurocode 6 [12]. The latter approach (engineered analysis and design according to Eurocode 6) needs to be followed for design of all buildings which do not meet the requirements for "simple buildings" as specified in Sections 9.2, 9.5 and 9.7.2 of Eurocode 8, Part 1. It should be noted that masonry walls designed according to either approach need to meet seismic detailing requirements prescribed in Section 9.5 of the code.

3 Rules for seismic design of simple masonry buildings: Wall Index

Rules for simple buildings outlined in Section 9.7 of Eurocode 8, Part 1 [7] prescribe the required amount of walls in each horizontal direction of the building plan, which is expressed as a percentage of the floor plan area ($p_{A,min}$), and is referred to as Wall Index (*WI*) in this paper; note that an alternative term "wall density" is also used in tehnical literature. *WI* for a given building can be determined as a sum of cross-sectional areas of all walls in the direction of considered earthquake action relative to the ground floor plan area (Figure 1), that is,

$$WI = \frac{A_w}{A_p}$$

where A_W is the cross-sectional area of walls with their lengths parallel to one direction at the ground floor level, and A_p is ground floor plan area. The required *WI* value for a specific building increases with the number of storeys (it is higher for taller buildings) and seismic hazard level, which is expressed as a product of design site acceleration ($a_g S$) and a corrective factor *k*. Note that the k value ranges from 1.0 to 2.0, depending on the average wall length. For example, $k = 1.5$ when average wall length is 4.0 m. Table 3 contains *WI* values for ordinary masonry buildings according to Eurocode 8, Part 1 (Table 9.3). The values were calculated assuming the minimum compressive strength for masonry units (e.g. modular clay blocks) of 5.0 MPa. For a three-storey ordinary masonry building, *WI* values range from 3.0 to 5.0 % when ground acceleration $a_g S$ increases from 0.07 to 0.15g (provided that $k = 1.0$). Note that the *WI* values presented in Table 9.3 are recommended values, however different values can be determined by a country-specific National Annex.

Table 3. Recommended allowable number of stories above ground and the required WI values for unreinforced/ordinary masonry buildings (Eurocode 8, Part 1)

Number of storeys	Acceleration at site $a_g S$			
	≤ 0.07*k·g*	**≤ 0.10*k·g***	**≤ 0.15*k·g***	**≤ 0.20*k·g***
1	2.0 %	2.0 %	3.5 %	n/a
2	2.0 %	2.5 %	5.0 %	n/a
3	3.0 %	5.0 %	n/a	n/a
4	5.0 %	n/a	n/a	n/a
Notes: n/a - not acceptable				

A *WI* value indicates seismic load-resisting capacity of a masonry building for the seismic force direction under consideration. A building must have sufficient shear capacity to resist the seismic forces at each storey level. The shear capacity depends on the number of shear walls in each horizontal direction, and the capacity of each wall to resist seismic forces. On the other hand, seismic demand, that is, applied seismic shear force at ground floor level, is resisted by the floor system (diaphragm) and then transferred to the individual walls. In most cases, masonry buildings have RC floors that act as rigid diaphragms. Consequently, internal seismic shear force in a specific wall is proportional to its stiffness relative to the sum of the stiffnesses of all walls aligned in the same direction. In low-rise masonry buildings, seismic behaviour of the walls is usually governed by shear. Shear stiffness of the wall is proportional to its cross-sectional area (length x thickness), and this can be used to establish the required ratio between the amount of walls (sum of cross-sectional areas of all walls in one direction) and the floor plan area. The above explanation is based on the strength-based design approach, which gives conservative (higher) *WI* values. Alternatively, *WI* values can be determined based on the displacement-based design approach which gives lower and more realistic *WI* values, but requires the knowledge of deformation-based nonlinear performance parameters for masonry walls.

Several research studies in countries like Mexico and Chile have confirmed correlation between the *WI* and the extent of earthquake damage in masonry and RC wall structures [14]. Chilean researchers have correlated the *WI* value and the observed damage for more than 280 masonry buildings affected by the 1985 Llolleo, Chile earthquake (M 7.8) [15]. The surveyed buildings were of reinforced, confined, and hybrid masonry construction. The buildings were one- to four-storey high. It was concluded that a minimum *WI* of 1.15 % or higher was required in each direction to avoid earthquake damage in these buildings. Masonry buildings with a *WI* per floor in the range of 0.50 to 1.15 % suffered moderate damage, while buildings with a *WI* per floor of less than 0.50 % suffered heavy damage. A study of confined masonry buildings affected by the 2010 Maule, Chile earthquake (M 8.8) showed that, in general, the buildings with a *WI* per floor of 0.9 % and higher remained undamaged, while buildings with a *WI* of 0.75 % or less experienced severe damage at the MSK shaking intensity of VII or higher [16].

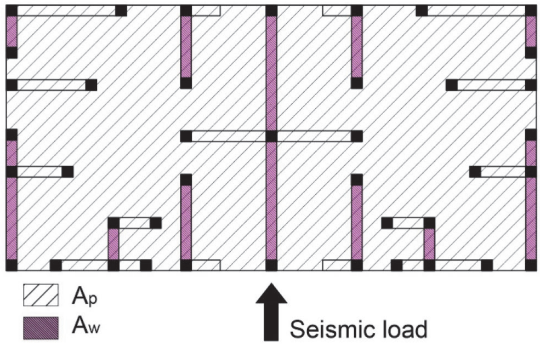

Figure 1. Input parameter for the Wall Index (WI) calculation (Brzev and Mitra 2018)

4 Case study of a masonry building damaged in the 2010 Kraljevo earthquake

The case study building is located in the Njegoševa Street No. 2 in Kraljevo, and it was damaged in the 2010 Kraljevo earthquake which caused 2 fatalities and more than $100 million in damages [17]. The building was constructed around 1950 as a 3-storey residential building with a basement and a half-floor at the top, see Figure 2a. The lower three floors have a plan with 22.2 m length and 16.0 m width. The top floor has smaller plan dimensions (11.0 m length and 10.9 m width). Typical floor height is 2.8 m. Walls at the lower 3 floors were constructed using 25 cm solid clay bricks in cement:lime mortar, while the walls at the top floor were constructed using modular clay blocks and concrete blocks. Floor and roof structures in the original building are ribbed RC slabs. Although the original construction documentation was not available, post-earthquake building survey confirmed the presence of RC tie-beams at each floor level. It is assumed that the building has RC strip footings. Floor plan at the ground floor level is shown in Figure 2b. Note that longitudinal walls are aligned in the N-S direction.

This is a loadbearing masonry structure typical for the post-World War II period. The walls are of URM construction and there are rigid floor/roof diaphragms. Since the building was constructed around 1950 it is assumed that seismic design was not performed. The building experienced moderate damage in the 2010 Kraljevo earthquake. The damage in the lower portion of the building was moderate. Minor cracking was observed in the walls aligned in transverse direction, mostly in the form of inclined cracks due to in-plane seismic effects. Horizontal cracks in longitudinal walls, particularly at the second floor level along gridline 5, were most prominent. These cracks were likely caused by the out-of-plane earthquake effects. The most significant damage was observed in the walls at the top floor level, particularly in partition walls constructed using modular clay blocks with horizontally aligned holes.

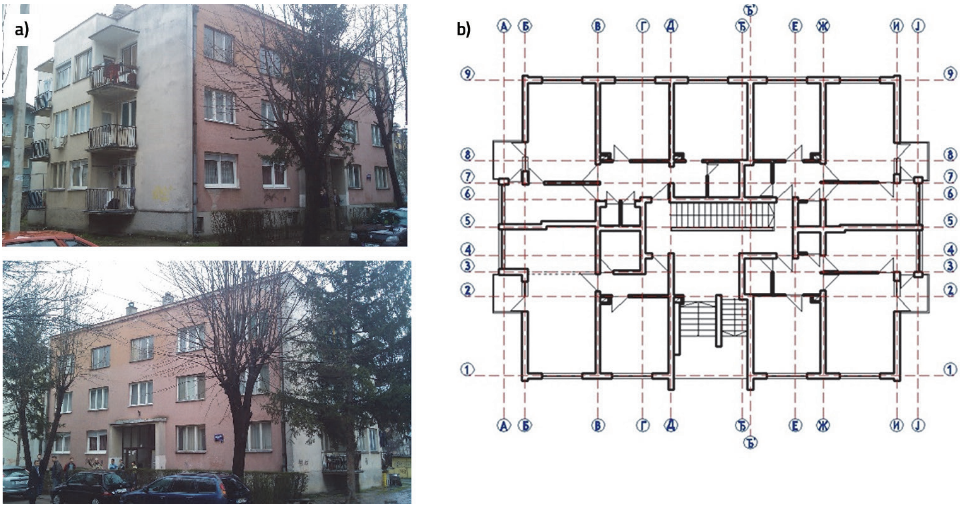

Figure 2. Case study building in Kraljevo, Serbia: a) exterior views and b) floor plan at ground floor level

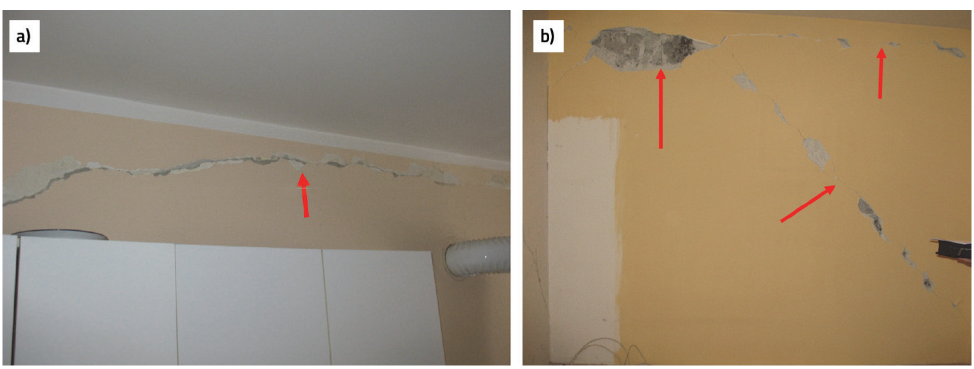

Figure 3. Earthquake damage patterns: a) horizontal crack at the wall-to-RC tie-beam interface, longitudinal wall (gridline 5) at the 2nd floor level and b) horizontal and diagonal cracks in a longitudinal wall (gridline 6 adjacent to the staircase), top floor level

Seismic evaluation of the building was performed to verify its seismic safety. The analysis was performed according to the seismic design code PTN-S [5] which was in place at the time of the earthquake. The building is located in seismic zone VIII according to the MCS scale [18]. Seismic forces were determined considering the following parameters: building category coefficient $K_o = 1.0$, seismic intensity coefficient $K_s = 0.05$, dynamic response coefficient $K_d = 1.0$, and ductility and damping coefficient $K_p = 2.0$. The ratio of seismic force at the base of the structure (V) and seismic weight (W), that is, V/W, is 0.09, which is the total seismic coefficient for this building. Since this is a low-rise building with rigid diaphragms, seismic forces were distributed to individual walls in proportion to their respective shear stiffness.

Seismic safety evaluation for masonry walls was performed according to the Allowable Stress Design approach per PTN-Z [10], and also according to the ultimate strength verification prescribed by PTN-S [5]. Since the mechanical properties of masonry were not known at the time of evaluation, the characteristic masonry compressive strength was determined based on the assumed mortar and brick compressive strengths according to PTN-Z [10], and the resulting f_k value was 2.4 MPa. The maximum allowable principal tensile stress of 0.09 MPa and the ultimate tensile strength of 0.18 MPa were prescribed by PTN-S [5]. The analysis results showed that the seismic safety of the building was satisfactory according to the current codes, both in terms of the allowable stresses and ultimate strengths.

This building has a regular plan shape and wall layout and could be treated as a simple masonry building according to Eurocode 8, Part 1 [7]. The WI values per floor were calculated as 5.27 and 3.11 % for transverse and longitudinal direction respectively. Based on the seismic hazard and number of storeys it is prescribed that the minimum WI value of 5 % needs to be ensured in each horizontal direction for a 3-storey URM building in seismic zone VIII; this corresponds to $a_g S$ value in the range from 0.1 to 0.2 g, depending on the wall length parameter k. The WI in longitudinal direction (3.11 %) appears to be significantly deficient according to Eurocode 8, Part 1 (5.0 %). Interestingly, the building experienced cracking in the longitudinal walls due to the 2010 Kraljevo earthquake, as discussed above.

5 Conclusions

Unreinforced (URM) masonry low- and mid-rise buildings constitute a significant portion of the housing stock in Serbia and other European countries. Multi-family URM buildings (usually 3-5 stories high) are of particular concerns due to higher occupancy and vulnerability to earthquake effects. Recent earthquakes in Albania (Nov 26, 2019 Durres earthquake) and Croatia (March 22, 2020 Zagreb earthquake and December 29, 2020 Petrinja earthquake) showed that multi-family residential URM buildings experienced damage and had to be vacated after the earthquake. Many buildings of this type which were constructed before 1964 were not designed for seismic actions. The paper presented an overview of past seismic design codes and provisions for URM structures which were used in Serbia and other countries which were a part of the former Yugoslavia.

Seismic design provisions for URM buildings contained in Eurocode 8, Part 1 have also been reviewed. The focus is on design provisions for simple buildings, which can be designed by following a simplified design procedure provided that the building is regular and that the minimum Wall Index (WI) requirement has been met.

Provisions of past seismic and masonry design codes from Serbia have been applied for seismic evaluation of a typical multi-family URM building which was damaged in the 2010 Kraljevo, Serbia earthquake. The study showed that the code requirements have been satisfied for the design seismic hazard level for the building site (zone VIII), although seismic design was likely not performed for this building. The design did not meet minimum WI requirements for simple masonry buildings based on Eurocode, Part 1 for walls in longitudinal direction. This deficiency is in line with the observed earthquake damage.

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