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SEISMIC RETROFITTING OF POST-WWII MID-RISE UNREINFORCED MASONRY RESIDENTIAL BUILDINGS IN THE BALKANS

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Abstract

There is a significant building stock of the existing low- and mid-rise unreinforced masonry (URM) buildings constructed after World War II in Serbia and neighbouring countries. Numerous buildings of this typology collapsed in the devastating 1963 Skopje, North Macedonia earthquake, causing fatalities, injuries, and property losses, and experienced damage in a few recent earthquakes in the region, including the 2010 Kraljevo, Serbia earthquake and the 2020 Petrinja, Croatia earthquake. These buildings are 3- to 5-storey high, have URM walls and rigid reinforced concrete (RC) or semi-prefabricated concrete and masonry floor slabs, usually with a RC ring beam at each floor level. The paper will provide an overview of seismic retrofitting approaches for these buildings, starting from provisions of design codes which were previously followed in Serbia and former Yugoslavia as well as Eurocode 8 (Part 3). Conventional seismic retrofitting technologies based on RC wall overlays which were applied in past earthquakes, including the 2010 Kraljevo earthquake, will be presented and their advantages and disadvantages will be discussed. Finally, a case study of a building in Kraljevo which was damaged in the 2010 earthquake and subsequently retrofitted, will be presented, including the results of seismic analysis and design solution. The paper should be of interest to engineers and academics interested in seismic retrofitting of masonry buildings.

Keywords: unreinforced masonry buildings; earthquake damage; seismic retrofitting; residential buildings.

1. Introduction

Masonry construction technology has been traditionally used for residential construction in European countries, including Serbia and the Balkan region [1,2]. Since the second half of 19th century construction of residential and public buildings in Serbia and the region has been performed using clay brick masonry. Reinforced concrete (RC) has been a technology of choice for construction of mid- and high-rise buildings since 1950s, however masonry has been widely used for low- to mid-rise residential construction in the region. According to the 2011 Census of Serbia [3], low-rise single family buildings constitute 95% of the national residential building stock, corresponding to 65.9% of all 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. According to the Census, 72% of all residential buildings in Serbia were constructed between 1946 and 1990, when Serbia was a part of the Socialist Federal Republic of Yugoslavia (SFRY), also known as “former Yugoslavia”. According to the Census, 72% of all residential buildings in Serbia were constructed between 1946 (after WWII) and 1990, when Serbia was a part of the Socialist Federal Republic of Yugoslavia (SFRY), referred to as “former Yugoslavia” in this paper (note that Croatia, Slovenia, North Macedonia, Montenegro, and Bosnia and Herzegovina were also a part of the former Yugoslavia). The majority of pre-1960 multi-family residential buildings were unreinforced masonry (URM) buildings, with load-bearing masonry walls as a structural system for resisting both gravity and lateral loads. Most of URM multi-family residential buildings of post-WWII vintage have semi-prefabricated RC floor systems. Buildings of this type constitute a significant fraction of the building stock in urban areas of Serbia and neighbouring countries and are the focus of this study. Examples of urban URM multi-family residential building from Serbia are shown in Fig. 1.

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a) b)

Figure 1. Examples of URM multi-family residential buildings in urban areas of Serbia: a) Belgrade and b) Niš.

Buildings of this typology were exposed to several damaging earthquakes in the region, including the 1963 Skopje, North Macedonia earthquake (M 6.0) (Fig. 2a), the 2010 Kraljevo, Serbia earthquake (M_W 5.5), and the 2020 Petrinja, Croatia earthquake (M 6.4) (Fig. 2b) [4, 5]. The buildings of this type which performed poorly in the 1963 Skopje earthquake were designed according to standardized designs, with load-bearing walls provided only in one horizontal direction (longitudinal or transverse) [6].


a) b)

Figure 2. Performance of URM multi-family residential buildings in past earthquakes in the region: a) a collapsed building due to the 1963 Skopje earthquake (credit: Z. Milutinović) and b) a damaged building due to the 2020 Petrinja earthquake (credit: SUZI-SAEE).

Urban areas of Serbia were not affected by major damaging earthquakes in the last 100 years, with the exception of the 2010 Kraljevo earthquake. A few other damaging earthquakes tool place in Serbia during the same period, namely the 1980 Kopaonik earthquake (M 5.8) and the 1998 Mionica earthquake (M 5.7), but they affected mostly rural areas. Consequently, design and construction experience in Serbia related to repair and seismic retrofitting of buildings in post-earthquake situations has been rather limited. The 2010 Kraljevo earthquake prompted a need for the repair and retrofitting of a significant number of damaged URM residential buildings. The main objective of the post-earthquake recovery was to restore damaged building infrastructure to its original pre-earthquake condition within a relatively short time frame and with limited financial resources. An additional constraint was to minimize the impact of construction activities on building occupants. As a result, the design and execution of seismic rehabilitation projects related to residential buildings used simple retrofitting techniques which were suitable for easy on-site implementation on a large scale. RC jacketing was selected because it was a well-established technique used for the structural strengthening of URM buildings in Serbia before the 2010 earthquake.

After the devastating 1963 Skopje earthquake, the first comprehensive seismic design code in the SFRY was published in 1964 [7]. A subsequent edition of the same code, PTN-S [8], issued in 1981, was the governing design code in Serbia until 2019. It was reported that the PTN-S code was at a similar level of advancement like other international seismic design codes at the time [9]. In 1982, deterministic seismic hazard maps for SFRY were issued as a companion to the PTN-S code, and were updated in 1987. The territory of Serbia was divided into zones VI to IX based on the MCS-64 seismic macrointensity scale. According to that map, majority of sites in Serbia, including Kraljevo, were assigned seismic zone VIII.

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Eurocodes were adopted as official codes for the design, construction, and maintenance of building structures in Serbia in 2019 [10]. As a result, Eurocode 8 – Part 1 [11] (also referred to as EC8-1 in this paper) is currently applied for seismic design of new buildings (SRPS EN 1998-1/NA:2018) [12]. An official seismic hazard map for Serbia was developed for design according to Eurocode 8 [13]. According to the map, the Peak Ground Acceleration (PGA) for a rock site (a_g) for design level earthquake with 10% probability of exceedance in 50 years is largest for Southern and Central Serbia (0.25g and 0.20g respectively), while other sites in Serbia were assigned lower PGA values. For example, Kraljevo was was assigned a_g value of 0.2g. Seismic design requirements for masonry buildings for Serbian codes and a comparison with the corresponding Eurocode 8 provisions were presented elsewhere [1], [2].

The first Yugoslav design code for repair, rehabilitation, and retrofitting of existing buildings was issued in 1985 (PTN-R) [14] based on the experience gained after the 1979 Montenegro earthquake, and it had been followed in Serbia until 2019. The code addressed seismic retrofitting of masonry and RC buildings and the foundations. Eurocode 8, Part 3 [15] (also referred to as EC8-3 in this paper) has been followed for seismic assessment and retrofitting of existing buildings in Serbia since 2019 (SRPS EN 1998-3/NA:2018, 2018) [16]. Annex C of EC8-3 contains specific provisions related to masonry buildings. In addition to the PTN-R code, which was the governing code for seismic retrofitting of buildings in Serbia until 2019, all masonry structures had to be designed or evaluated according to the PTN-Z code which was issued in 1991 [17]. Similarly, Eurocode 6 (EN 1996-1-1:2004) [18], which is currently used in Serbia [19], contains design provisions for masonry buildings.

In this paper, the authors have shared lessons related to seismic retrofitting of URM buildings damaged in the 2010 Kraljevo, Serbia earthquake. Various seismic retrofitting techniques for URM buildings have been discussed, but the focus is on of RC jacketing, a common seismic retrofitting technique for URM buildings which has been used in Serbia and other countries. The authors have presented selected results of seismic analysis and retrofitting design for a typical URM building in Kraljevo, which was damaged due to the 2010 earthquake and subsequently retrofitted. A comparison of the capacity/demand ratios has been performed for the original and retrofitted building, according to both the Yugoslav seismic design and retrofit codes and Eurocode 8. The results of the study showed that the implemented retrofit solution satisfied the Yugoslav seismic code requirements, but it is not adequate according to the Eurocode 8 requirements. Findings of the paper may be particularly of interest to engineers in the Balkan countries, which recently adopted Eurocode 8 as the governing code for seismic design of new buildings and evaluation/retrofitting of existing buildings.

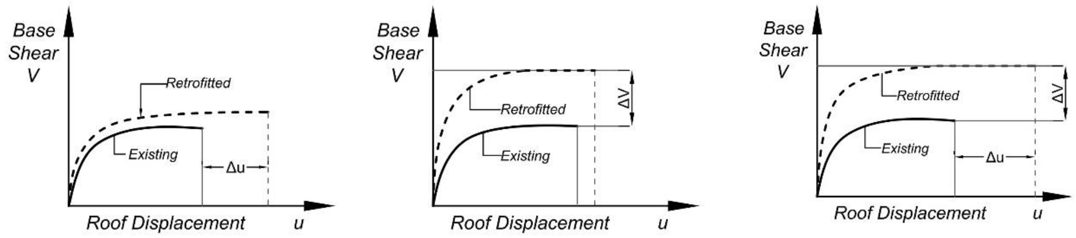
2. Seismic retrofitting techniques for URM buildings

2.1 Seismic retrofitting objectives and goals

Seismic retrofitting solutions should be effective in enhancing the performance of existing structures to achieve predetermined performance objectives. Performance ob-jective(s) for a specific structure are either set by a seismic design code or project-specific criteria. In some countries, technical codes/standards for existing buildings may permit relaxed seismic performance objectives for the evaluation and retrofitting of existing buildings relative to the design of new structures, e.g. ASCE/SEI 41-17 code in the USA [20]. In the context of a specific project, these performance objectives are either prescribed by the seismic codes, or they are defined by project-specific criteria. According to the PTN-R code, similar to other older seismic codes, the main performance objective for rehabilitated or strengthened buildings was same as for new structures: structural damage due to a major damaging earthquake was acceptable, but the collapse had to be avoided. On the other hand, EC8-3 contains elements of modern approaches such as Performance-Based Earthquake Engineering (PBEE), hence performance objectives have been specified by the code. For example, capacity models for assessment of existing buildings considered for the limit states “near collapse”, “significant damage”, and “damage limitation”, as outlined in Eurocode 8.

One of the key design aspects of a seismic retrofitting project is to identify retro-fitting goal(s). After the seismic evaluation of a building is performed and the defi-ciencies have been identified, a designer should be able to determine the retrofitting goal(s). Is the main goal of the retrofitting to enhance the lateral load-resisting capacity and/or stiffness and/or ductility of the existing structure - or perhaps a combination of those structural characteristics? An appropriate seismic retrofitting solution may be selected after the goals have been established.

Retrofitting may be able to enhance lateral load-resisting capacity and/or stiffness and/or ductility of the existing structure, as shown in Fig. 3 [21]. In many cases, the primary goal of retrofitting is to enhance the ductility of the existing structure, which may be feasible for retrofitting of older RC structures (Fig. 3a). Alternatively, stiffness and capacity enhancement (Fig. 3b) may be feasible for retrofitting of an existing non-ductile structure. Stiffness, capacity, and ductility enhancement (illustrated in Fig. 3c) may be feasible for existing buildings with high seismic demand, which prompts a need for increased lateral load-resisting capacity. In the context of URM structures, it is important to note that it is unlikely for a retrofitting solution to achieve a significant increase in ductility due to the brittle nature of masonry. It is expected that a typical global retrofitting solution for a URM structure should primarily be effective in increasing its lateral load-resisting capacity. Several researchers have studied different seismic retrofitting techniques for masonry buildings and compared their effectiveness [22-25].



a) Ductility Enhancement

b) Stiffness and Strength Enhancement

c) Stiffness, Strength & Ductility Enhancement

Figure 3. Seismic retrofitting goals [22].

2.2 An overview of seismic retrofitting techniques for masonry buildings

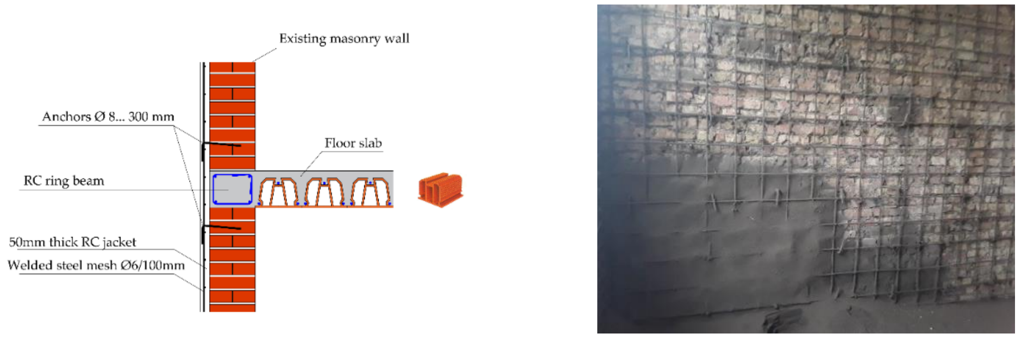
Seismic retrofitting projects in the Balkan region were initiated after the 1979 Montenegro earthquake (M 6.9), which caused damage and collapse of buildings in coastal areas of Montenegro and Croatia. Engineers and academics from all parts of the former Yugoslavia participated in the planning, design, and construction supervision of post-earthquake recovery. The earthquake also prompted a few relevant regional projects, which engaged experts from neighboring countries, such as the UNIDO-sponsored project "Building Construction Under Seismic Conditions in the Balkan Region". A series of comprehensive technical resources were produced as a result of the project, including the guidelines for seismic retrofitting of existing RC and masonry buildings [26]. Notable experimental research studies and field applications of seismic retrofitting on existing masonry buildings were performed by Prof. Miha Tomaževič and his colleagues at ZAG, Slovenia [25, 27]. Comprehensive technical guidelines have recently been developed for repair and retrofitting of masonry buildings affected by the March 2020 Zagreb, Croatia earthquake [28]. A valuable resource is available in Serbia for engineers engaged in structural and seismic rehabilitation of buildings [29].

The most common retrofitting approaches for URM structures include: i) retrofitting of existing masonry walls by means of thin overlays, ii) construction of new RC walls attached to the existing masonry walls, iii) retrofitting of intersecting wall connections, and iv) retrofitting of the existing floor and/or roof structures and the wall-to-floor connections. In some cases, retrofitting of existing foundations may also be required (when shear and/or flexural capacity of the retrofitted wall have increased as a result of the retrofit). It should be noted that approaches i) and ii) are related to enhancing lateral load-resisting capacity of individual masonry walls, while approaches iii) and iv) are related to enhancing the integrity of entire building. Since the focus of this study are URM buildings constructed with clay brick masonry walls and rigid floor systems, it can be expected that in most cases only approaches i) and ii) need to be implemented. Approach iii) may need to be implemented in case of low-strength masonry (e.g. stone masonry structures), or when bond between the intersecting walls is inadequate (which is often the case in building expansions). Finally, approach iv) may be required in case of flexible (timber) diaphragms, or prefabricated hollow-core RC slabs. Therefore, this section is focused mostly on approaches i) and ii), with the main focus on RC jacketing as a widely used seismic retrofitting technique in the region, as well as in other parts of the world.

2.3 Common retrofitting techniques for the existing URM walls

Seismic retrofitting of URM walls is performed to enhance their in-plane and/or out-of-plane seismic capacity/resistance. As discussed in the previous section, common retrofitting techniques involve application of new coatings/overlays, which are attached/bonded to an existing masonry wall. These overlays can be classified based on their thickness into thin and thick. Thin overlays (also known as surface coatings) consist of cement-based coating reinforced with steel mesh reinforcement, which is also known as RC jacketing or reinforced plaster; alternatively, a thin coating may consist of Fiber Reinforced Polymer (FRP) strips or fabrics which are bonded to an existing wall by means of epoxy resin (or alternative). Thick overlays are in the form of new RC walls which are attached to an existing masonry wall by means of steel anchors embedded into the wall. There is no hard rule regarding the maximum thickness for thin cement-based coatings, but the thickness usually ranges from 3-8 cm, while the thickness of thick RC overlays may range from 10-30 cm.

RC jacketing technique (Fig. 4) consists of constructing one- or two-sided RC jackets attached to exterior and/or interior wall surfaces [22, 27]. A jacket consists of a 3 to 8 cm thick concrete overlay with reinforcement in the form of steel mesh (usually small-sized bars, 4 to 10 mm diameter). RC jackets are usually attached to an existing masonry wall via steel anchors inserted in pre-drilled holes, which are subsequently filled with cement- or epoxy-based grout. The required size and spacing of anchors depends on seismic demand (shear force) that needs to be transferred from the jackets to the original masonry wall. Either cast-in-place concrete or sprayed concrete (shotcrete) can be used for construction of RC jackets.



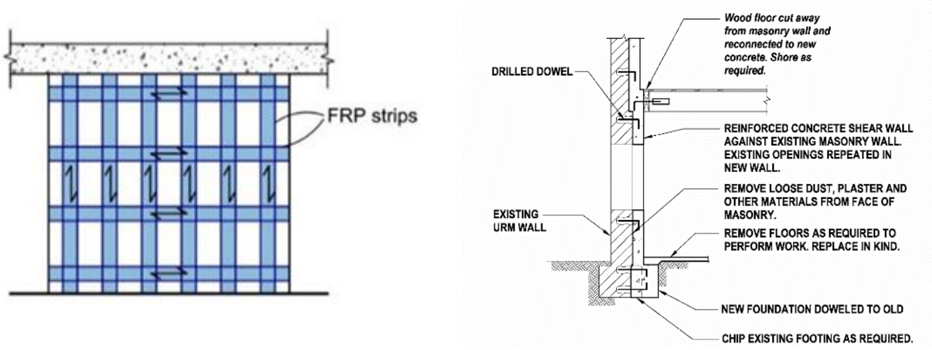
a) b)

Figure 4. RC jacketing: a) vertical section of a retrofitted wall in Kraljevo, Serbia and b) shotcrete application in a retrofitted school building in Kyrgyzstan [22].

Several experimental research studies on masonry wall specimens subjected to monotonic and/or reversed cyclic lateral loading have shown a significant increase in the shear capacity and stiffness of URM walls retrofitted using RC jacketing [31-36]. The results confirmed that RC jacketing was able to increase lateral capacity of the specimens by a factor of 2.0 to 3.0. Specimens with two-sided jacketing showed higher ductility and energy dissipation capacity compared to one-sided jacketing. The results of extensive experimental research studies on masonry walls with RC jacketing by Prof. Miha Tomaževič in Slovenia showed an increase in shear strength by 1.3 to 3.6 for retrofitted walls [27]. A research study involving shaking table testing of a four-storey masonry building model retrofitted with RC jacketing was performed at IZIIS, Skopje [37].

Seismic retrofitting of masonry walls can also be achieved by applying thin Fiber Reinforced Polymer (FRP) overlays or strips on wall surfaces that were previously saturated by epoxy resin (or alternative) [22, 38]. A FRP overlay is typically made of glass or carbon fibers in an adhesive matrix. FRP overlays may cover the entire wall surface, or applied in the form of strips aligned in horizontal, vertical, or diagonal directions (Fig. 5). FRP overlays and strips can be used either as one-sided or two-sided applications. These overlays are very thin and light-weight (overall thickness on the order of few milimeters). To ensure an adequate anchorage, these FRP overlays/strips can either be wrapped (extended) at the wall ends, or custom-designed fiber anchors can be installed along the wall perimeter. Polymer fibers act as tension reinforcement for the wall and should be aligned in the direction of tensile stresses. The required effective area of fibers per unit width and the FRP contribution to shear capacity of a retrofitted wall are governed by bond and anchorage strength at the FRP-to-wall interface. Design procedures for FRP-based retrofitting of masonry structures are well established [39]. Experience related to the application of FRP technology in Serbia and the region is limited, however this technology has been recently used for retrofitting of masonry buildings after the 2020 Zagreb, Croatia earthquake [40].

When an existing URM wall has a deficient gravity and lateral load-resisting capacity, it can be retrofitted by constructing a thick RC overlay (new RC shear wall) which is attached to the existing masonry wall [41]. The concept is essentially similar to RC jacketing. Addition of a new RC wall results in a significant increase in lateral stiffness, shear and flexural capacity of the existing wall. A new RC wall is attached to the existing masonry wall in the same manner as previously explained for RC jacketing, except that the amount of wall reinforcement and anchors may be different. Retrofitting of wall foundations is usually required due to a significant increase in the shear and flexural capacity of a retrofitted wall.



a) b)

Figure 5. Techniques for seismic retrofitting of masonry walls: a) thin overlays – FRP strips [22] and b) thick overlay (new RC shear wall) [38].

Design of a masonry wall retrofitted by overlays is performed by considering stiffness of the retrofitted wall as the sum of the stiffnesses of the original masonry wall and the overlays. An example of a retrofitted URM wall with two-sided RC jackecting is presented in Fig. 6. Internal shear force in an RC jacket (Q_B) is obtained when the total force Q is multiplied by a ratio of the jacket stiffness (K_B) relative to the total wall stiffness (K_Z+2 K_B). Note that the stiffness of an RC jacket is influenced by its thickness and the mechanical properties of concrete (modulus of elasticity E_c and modulus of rigidity G_c) – stiffness of reinforcement does not need to be considered.

Verification of lateral load-resisting capacity of a retrofitted wall with RC jackets needs to be performed by verifying the capacity of a composite section. For example, capacity of a masonry wall needs to be determined based on the applicable code equations and subsequently compared with the corresponding demand (shear force Q_Z and the corresponding axial force and bending moment). On the other hand, shear capacity of an RC jacket needs to be determined based on the shear contribution of steel mesh, while the concrete contribution may be ignored. The corresponding shear demand for an RC jacket is Q_B (as explained earlier in this section). It should be noted that PTN-R code prescribed a simplified procedure for determining shear capacity of an URM wall with RC jackets, which considered a retrofitted wall as an equivalent masonry section, with the thickness equal to the sum of thicknesses of masonry wall (t_Z), plus thickness of each RC jacket (t_B).

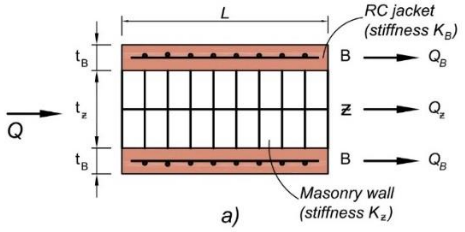


Figure 6. Internal force distribution in a retrofitted URM wall with RC jackets [23].

3. Seismic retrofitting of damaged URM buildings after the 2010 Kraljevo earthquake

3.1 Performance of mid-rise URM buildings in the earthquake

Several multi-family URM buildings (3- to 5-storey high) constructed after WWII (1945-1963) were damaged in the earthquake and required repair and retrofit [41, 42]. Masonry walls were typically constructed using solid clay bricks and their thickness ranged from 25 cm (interior walls) to 38 cm (exterior walls). The floors were ribbed RC slabs, and RC tie-beams (ring beams) were provided at each floor level. In most cases the walls experienced moderate damage in the form of cracks due to in-plane or out-of-plane seismic loads. The damage patterns observed in these buildings after the earthquake were discussed in a few publications [4, 41]. Some of the damaged buildings had vertical extensions (additional floors). It was reported that the extensions which were not compliant with the technical regulations were damaged in many cases [43].

This section discusses a typical URM building in Kraljevo which was damaged in the 2010 earthquake and was subsequently retrofitted by applying RC jacketing, in compliance with the PTN-R code that was used in Serbia and former Yugoslavia since 1985. The building is located in the Njegoševa Street No. 2 in Kraljevo, and was constructed around 1950 as a 3-storey residential building with a basement and a half-floor at the top, and a typical storey height of 2.8 m, see Fig. 7. Walls at the lower 3 floors were constructed using 25 cm solid clay bricks in 1:3:9 cement:lime:sand mortar, while non-structural walls at the top floor were constructed using 120 mm thick modular (multi-perforated) clay blocks. In the absence of material testing data M25 class bricks (2.5 MPa compressive strength) were assumed for the original building and M100 class modular blocks (10 MPa compressive strength) for the extended top floor.

Floors and roof were constructed using semi-prefabricated composite masonry and concrete system (see Fig. 4a), and were considered to act as rigid diaphragms. RC tie-beams were provided at each floor level. Since the building was constructed around 1950, seismic actions were likely not considered in the original design. The building was damaged in the 2010 earthquake. Structural damage in lower portion of the building was mostly in the form of inclined cracks due to in-plane seismic effects. Refer to [2] for more details related to seismic performance of the building in the 2010 Kraljevo earthquake and a detailed seismic evaluation of the damaged structure according to the PTN-S code and Eurocode 8.

The building was retrofitted according to the PTN-R code. The main goal of seismic retrofitting was to enhance the overall structural integrity, by constructing vertical RC jackets along the façade, embellished in blue colour on the floor plan in Fig. 8. The main reason for performing exterior retrofitting (at the façade) was to minimize disruption to the building occupants. Many earthquake-damaged URM buildings in Kraljevo were retrofitted using the same approach. Refer to [44] for more details related to the seismic evaluation and retrofitting design for this building.

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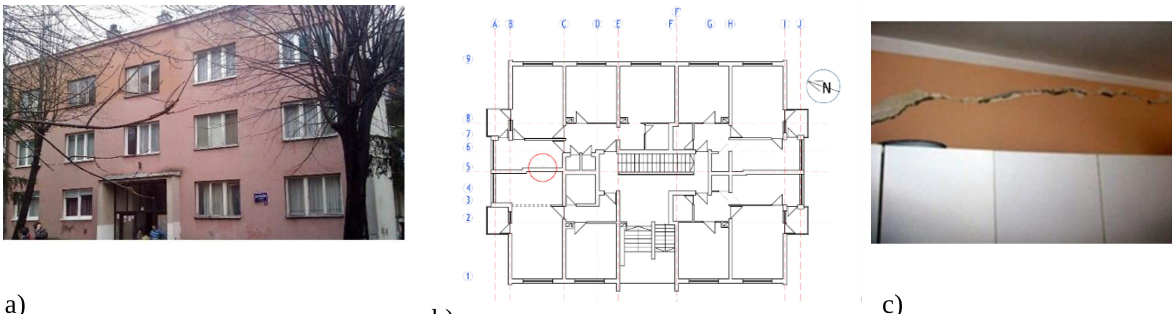

a) b) c)

Figure 7. URM building located in the Njegoseva Street No.2, Kraljevo: a) west façade; b) typical floor plan, and c) severe cracking in a longitudinal wall at the 2nd floor level (gridline 5).

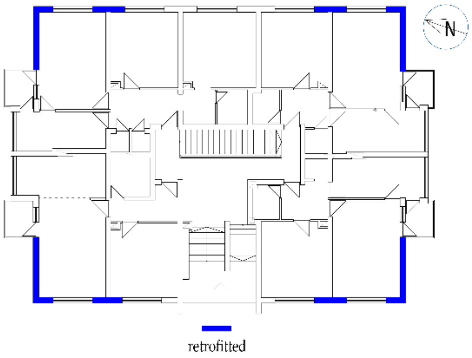

Figure 8. Typical floor plans showing locations of RC jackets.

3.3 Seismic analysis of the original and the retrofitted building

Seismic evaluation and retrofit design of earthquake-damaged buildings in Kraljevo was performed in line with the technical regulations which were enforced in Serbia at the time of the 2010 earthquake, that is, PTN-S and PTN-R. These codes prescribed linear elastic analysis for both the original and retrofitted structures. The effect of nonlinear seismic response of cracked URM walls was considered in line with the EC8-3 provisions for masonry buildings (by reducing the wall stiffness), but nonlinear seismic analysis was not performed.

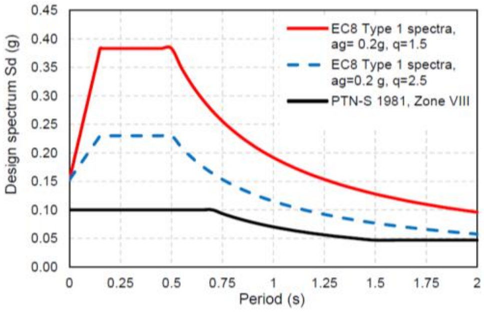

Figure 9. Design response spectra for Kraljevo, Serbia according to Eurocode 8 and PTN-S code.

Equivalent static seismic analysis according to the PTN-S code was performed using the following parameters: seismic intensity coefficient Ks of 0.05 (seismic intensity zone VIII), building category coefficient K_o of 1.0 corresponding to Category I, dynamic response coefficient K_d of 1.0, and the ductility and damping coefficient K_p of 2.0 (corresponding to URM building). The soil was classified as Category II according to the PTN-S code. It should be noted that seismic hazard parameters for Kraljevo were revised after the earthquake, hence the building site is currently located in seismic intensity zone IX. Multi-modal seismic analysis was performed for both the original and retrofitted structure according to EC8-1. The design ground acceleration for soil type A was 0.2g, while ground type B was considered for the site. Spectral accelerations for the elastic design spectrum Sd(T) according to Eurocode 8 were divided by the behaviour factor q of 1.5 for URM structures designed without seismic provisions (for original structure) and q= 2.5 (for retrofitted structure). Type 1 spectrum was deemed appropriate, given the seismic hazard setting for the building site. Design response spectra for Kraljevo, Serbia, based on the PTN-S code and Eurocode 8 are presented in Fig. 9.

A 3-D numerical model of the building was created using the Tower software package by considering the walls as shell finite elements and slabs as plate elements. Floor and roof structures were treated as rigid diaphragms, which the foundations were simulated as fixed-base restraints. A cantilever numerical model, which considered only wall piers (no spandrels) was developed for the original structure because it resulted in a more conservative seismic force demand compared to an alternative Equivalent Frame Model. Modulus of elasticity for masonry was taken as 2410 MPa. Dynamic properties of the numerical model were obtained as a result of modal analysis. The seismic masses were calculated according to the PTN-S code. Fundamental period for the longitudinal (N-S) and transverse (E-W) directions were 0.267 sec and 0.20 sec respectively.

According to the PTN-R code, a retrofitted masonry wall with an RC jacket was modelled as an equivalent masonry wall with the thickness equal to thickness of the original wall plus additional thickness (equal to 4 times the thickness of an RC jacket). According to the EC8-3 code, the designer is expected to simulate the effect of an RC jacket by modelling it as a separate shell layer, or a part of a composite equivalent column section, where masonry and concrete materials would be simulated using appropriate mechanical and geometric properties. Numerical models for the original and retrofitted structure are shown on Fig. 10.

The following three models were considered to account for the effect of cracking on the original and retrofitted structure: a) Model 1, which considered uncracked (gross) properties of the original structure in line with PTN-S code (referred to as Original 1 and Retrofitted 1); b) Model 2, which considered the effect of moderate cracking (20% stiffness reduction), which is referred to as Original 2 and Retrofitted 2, and c) Model 3, which considers 50% stiffness reduction in line with EC8-3 (Original 3 and Retrofitted 3).

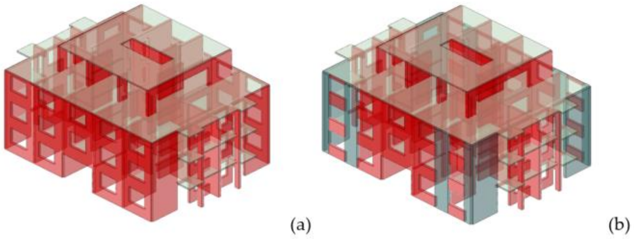

Figure 10. Numerical models: a) original structure and b) retrofitted structure.

To illustrate the effectiveness of retrofitting, seismic base shear force V_{Ed} (kN) (seismic demand) was compared with the shear capacity at the ground floor level V_{Rd} (kN), which was taken equal to the sum of capacities for all walls aligned in the same direction (N-S or E-W). The results for longitudinal (N-S) direction are illustrated in Fig. 11. It can be seen from the chart that the capacity of the building was satisfactory according to the PTN-S, since the capacity (C) versus demand (D) ratio, C/D, is larger than 1.0 both for the Original 1 (uncracked) model (in line with the PTN-S) and the Original 2 model (cracked, 20% stiffness reduction), but it is not satisfactory for the Original 3 model (cracked, 50% stiffness reduction – in line with EC8-3). The results also indicate that, according to the PTN-S code, the retrofit has resulted in an increased C/D ratio for the building to 1.52, 1.22, and 0.76 for Models 1, 2, and 3, respectively. The results indicate that the Retrofitted 3 model (which considers 50% stiffness reduction) is not satisfactory, since the corresponding C/D value is less than 1.0. The analysis performed according to the EC8 requirements showed that the capacity of the structure is not satisfactory even after the retrofit for Model 3, which is in line with the EC8-3 (C/D < 1.0); however, the retrofit solution seems to be effective for Model 1 (in line with the PTN-S code), since the corresponding C/D ratio is 1.03.

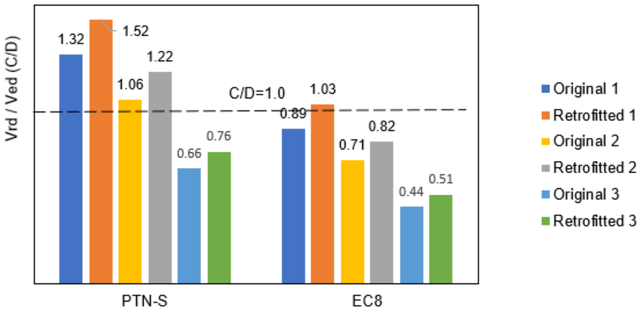

Figure 11. Seismic capacity versus demand (C/D) ratio for the ground floor of the building in N-S direction (for the original and retrofitted building).

4. Conclusions

The paper presents a study on seismic retrofitting of URM mid-rise residential buildings of post-WWII vintage, which are typical for the Balkans, in particular Serbia and neighbouring countries. An overview of common seismic retrofitting solutions for URM walls has been presented, and a typical building damaged in the 2010 Kraljevo earthquake and subsequently retrofitted using RC jacketing technique was analysed. A comparison of the results for seismic analyses performed according to the Yugoslav seismic codes and Eurocode 8 has shown that the seismic demand according to Eurocode 8 is significantly higher compared to the Yugoslav seismic codes PTN-S and PTN-R, which were used for seismic evaluation and retrofitting design. The key finding is that the retrofitting design solution performed according to the Yugoslav seismic codes for a URM building in Kraljevo does not meet the seismic safety requirements of Eurocode 8. In order to satisfy the seismic demand requirements according to Eurocode 8, a more extensive retrofitting would be required, most likely applied to interior walls - in addition to exterior walls which were retrofitted according to the original solution.

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