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Source / Izvornik: **Bulletin of earthquake engineering, 2023, 21, 4315 - 4383**

Journal article, Published version

Rad u časopisu, Objavljena verzija rada (izdavačev PDF)

<https://doi.org/10.1007/s10518-023-01676-0>

Permanent link / Trajna poveznica: <https://urn.nsk.hr/urn:nbn:hr:133:190657>

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Download date / Datum preuzimanja: **2025-02-28**



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Residential building stock in Serbia: classification and vulnerability for seismic risk studies

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Received: 29 November 2022 / Accepted: 15 March 2023 / Published online: 10 April 2023
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Abstract

Regional seismic risk assessment is necessary for designing effective seismic risk mitigation measures. In general, such risk assessment studies consist of three components: hazard, vulnerability, and exposure modelling. This paper lays the foundations for regional seismic risk assessment of the residential building stock in Serbia and addresses each of the three seismic risk assessment components, either by reviewing the existing or proposing novel models. First, a review of seismic hazard models and seismic design codes used in Serbia in the past 70 years was presented. Next, an overview of Serbia's population metrics and historical development of Serbian's residential building stock was presented to provide the context for the exposure model. Furthermore, the paper proposed a novel building classification for Serbia's residential building stock, which is based on the existing building taxonomies, but it has been adapted to account for the local building characteristics. Building damage patterns reported in past earthquakes in Serbia and neighbouring countries were reviewed as a basis for damage classification pertaining to building typologies included in the proposed classification. Finally, the results of a preliminary vulnerability model were presented in the form of expert-based fragility functions derived for buildings typical of Serbia's residential building stock.

Keywords Residential buildings · Seismic risk assessment · Building classification · Fragility functions

1 Introduction

Seismic risk assessment is the first step towards seismic risk mitigation for a city, country, or region, and consists of hazard, exposure, and vulnerability modelling. Hazard models provide estimates for the expected earthquake intensity measures within a region, while the exposure models provide information on the number, type, and value of assets (e.g., buildings) exposed to earthquakes. Vulnerability models provide a mapping from earthquake

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intensity measures to expected damage and losses. The results of seismic risk assessment studies inform seismic risk mitigation actions by providing estimates of potential losses due to future earthquakes and identifying vulnerable building typologies and areas with high seismic risk.

This study aims to make the first step towards seismic risk assessment for Serbia. Although exposed to moderate seismic hazards, seismic risk assessment studies focused on Serbia and the region are limited. The composition and vulnerability of the building stock in Serbia are similar to neighbouring countries (Slovenia, Croatia, Bosnia and Herzegovina, Montenegro, and North Macedonia), which used to be a part of Yugoslavia until the 1990s. Due to the similar building stock, lessons learned from past earthquakes in these countries and the findings of seismic risk studies are relevant for Serbia.

Milutinovic et al. (2022) performed a study on the evolution of seismic design codes in former Yugoslavia since 1948 and their impact on the seismic vulnerability of buildings. Lutman et al. (2014) reviewed the efforts to assess and mitigate seismic risk in Slovenia and reported a seismic risk assessment study for Ljubljana, the capital of Slovenia. Furthermore, several seismic risk awareness and mitigation tools were developed, including a web application to inform citizens about the vulnerability of their buildings, a tool for early post-earthquake damage assessment, and a support system for post-earthquake building safety evaluation. Šket Motnikar et al. (2022) recently presented the 2021 seismic hazard model for Slovenia, while Babič et al. (2021) showed that a repeat of the 1895 M6.2 Ljubljana earthquake would result in direct losses amounting to 15% of the national GDP.

The first earthquake loss assessment study in Croatia was performed by Aničić (1992) and it was focused on the city of Zagreb, the capital of Croatia. A detailed overview of earthquake risk studies for Croatia was presented by Hadzima-Nyarko and Kalman Šipoš (2017). The earthquakes that hit Zagreb (March 2020) and Petrinja (December 2020) brought attention to Croatia's challenges related to the lack of activities and strategies to mitigate earthquake risk. The consequences of these earthquakes were outlined in several publications (Šavor Novak et al. 2020; Atalić et al. 2021; Stepinac et al. 2021), while the post-earthquake damage assessment process was explained by Uroš et al. (2020).

A few research studies related to the seismic vulnerability of building stock in Bosnia and Herzegovina are also available (Ademović 2011; Ademovic et al. 2013; Ademović et al. 2019). The vulnerability index method was used as an empirical method to estimate the seismic vulnerability of masonry buildings in major urban centres of the country (Ademović et al. 2022). An ongoing research study in Sarajevo, the country's capital, is focused on developing a database of 700 structures in two selected municipalities as the starting point for the development of the national building taxonomy (Piljug et al. 2022).

Seismic loss assessment for a scenario earthquake was performed for the city of Bitola, North Macedonia within the framework of the RISK-UE project from 2001. to 2004. (Mouroux et al. 2004). Mircevska et al. (2022) presented a seismic loss assessment study for Skopje, the capital of North Macedonia. They estimated that a repeat of the 1963 Skopje earthquake would result in significant direct losses, estimated at \$US 6.8 billion and more than 1900 collapsed or severely damaged buildings.

This paper presents the results of an initial study intended to serve as the basis for the development of a seismic risk model for Serbia. A review of seismic hazard models and the evolution of building codes in Serbia are presented in Sect. 2. Section 3 presents the historical context, population and building stock information for Serbia, which are crucial for developing a reliable exposure model. Exposure models also require a classification of the building stock. Regional risk assessment studies often include tens of thousands of buildings; hence it is not feasible to consider each building as an isolated element of the

built environment. Therefore, buildings need to be classified based on their structural characteristics which are relevant for estimating their seismic vulnerability. Section 4 proposes a novel classification system for the Serbian residential building stock based on the existing building taxonomies and the local context. Section 5 reviews evidence related to building damage due to past earthquakes in Serbia and neighbouring countries, while Sect. 6 provides non-rigorous expert-based fragility functions for the Serbian building stock, as a starting point for the development of a more refined building vulnerability model.

2 Seismic hazard and building codes in Serbia

2.1 Seismicity and seismic hazard

The Republic of Serbia is located in the central-western Balkans and is surrounded by the Pannonian Basin at the north-west, Dinaric Alps at the south-west, Balkan Mountains, Rhodopes at the south-east, and the Carpathian Mountains at the north-east (see Fig. 1). Most of the seismicity in Serbia is intraplate, and normal faults are more widespread than for example in the External Dinarides, where thrusts and strike-slip faults account for nearly all seismic events. The depth of the Moho rises from 25 km beneath the Pannonian Basin to 45 km beneath the Dinarides (Skoko et al. 1987; Bielik et al. 2018). Though the

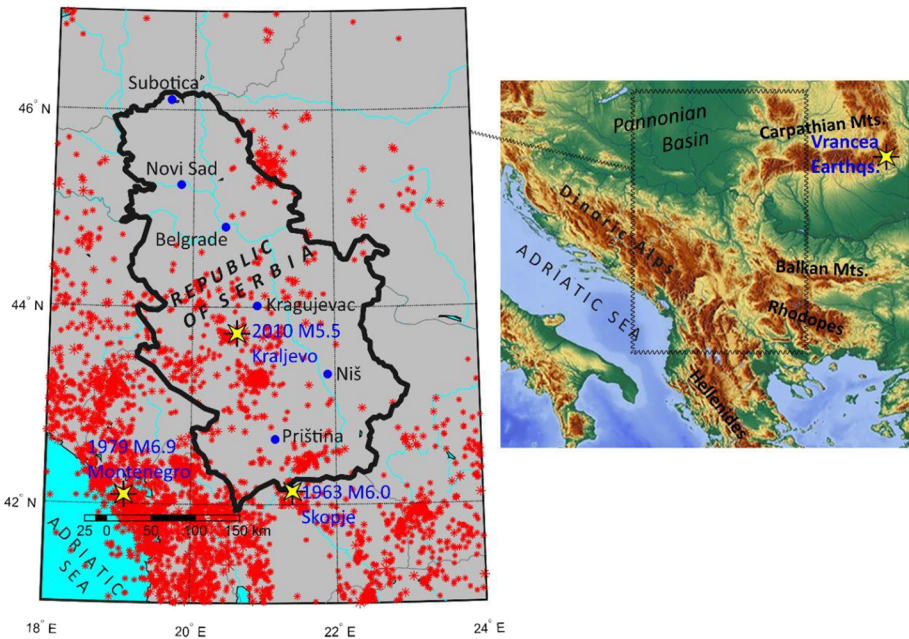


Fig. 1 Earthquakes in Serbia and the region. **a** Epicenters of the regional earthquakes with $M_w \geq 3.0$, recorded between 1900 and 2021 (USGS 2021), including the epicenters of the most significant seismic events from 1963-present, and **b** a geographic map of Serbia (shown within the frame) and the Balkan region, showing the location of the Vrancea, Romania seismic source zone

level of seismic activity is not evenly distributed, the entire territory of Serbia is seismically active, and seismic risk has to be estimated for all parts of the country.

Figure 1 shows the epicentres of the regional earthquakes with $M_w \geq 3.0$, which were recorded from 1900 to 2021 (USGS 2021). North Serbia is in the southern part of the Pannonian Basin, where larger seismic events are very rare (Morales-Esteban et al. 2021). On the other hand, southern parts of the country border the Mediterranean-Trans-Asian belt, which is characterised by the relatively frequent occurrence of stronger events. The two most devastating earthquakes in Yugoslavia occurred in that region, namely the July 26, 1963, M6.0 Skopje Earthquake and the April 15, 1979, M6.9 Montenegro Earthquake (Fig. 1).

In the twentieth century, a series of earthquakes occurred in central Serbia and caused damage mostly in rural areas, including the 1922 M6.0 Lazarevac, 1927 M5.9 Rudnik, 1980 M5.8 Kopaonik, and 1998 M5.7 Mionica earthquakes. The most recent significant earthquake in Serbia was the November 3, 2010, M5.5 Kraljevo Earthquake with an epicentral intensity of VII-VIII °MCS (Fig. 1). It was reported that 2 people died, approximately 180 people were injured, and close to 16,000 structures experienced damage due to the 2010 Kraljevo Earthquake (RTS 2012). Besides the local seismicity, the territory of Serbia is affected by the distant and very strong Vrancea earthquakes, with the epicentral location shown in Fig. 1. A recent seismic micro-zonation study for the City of Belgrade has shown that the peak ground acceleration (hereinafter, PGA) amplitudes are expected to be dominantly influenced by the local seismicity and are not particularly sensitive to Vrancea events (Lee et al. 2017). This is because the short-period seismic waves attenuate quickly and when travelling from longer distances their contribution is lower than the contribution of the local events (Lee et al. 2016). However, the same study has shown that the long-period waves are significantly affected by the strong Vrancea earthquakes, especially when deep geological sediments are present below the local soil (Lee et al. 2017). It should also be noted that reinforced-concrete (RC) and masonry structures, such as those found in Serbia, could be significantly impacted by the earthquake source directivity phenomena (i.e., the presence of high-velocity pulses). Yet, this will remain outside the scope of our current study because regional strong motion databases do not comprise enough near-field records related to previous devastating earthquakes.

2.2 An overview of seismic design codes

Until 2019, seismic design codes developed in Yugoslavia (before its breakdown in 1991) were enforced in Serbia. The first Yugoslav seismic design code, issued in 1948 (PTP-2 1948), did not contain specific detailing provisions for RC and masonry structures, and seismic design forces were applied as a static load. A ratio of the total design force (V_b) and building weight (W), that is, the V_b/W ratio, ranged from 1 to 2%, depending on the type of structure and seismic intensity.

In 1964, shortly after the devastating 1963 Skopje Earthquake, the first comprehensive Yugoslav seismic design code was issued (PTP-12 1964). The Modal Analysis method was prescribed for the seismic design of flexible structures, while rigid structures could be designed using simplified methods. The design seismic forces were determined based on the building occupancy, seismic intensity, soil type (3 categories), and dynamic properties (fundamental period); the type of structural system and expected ductility level were not considered. The V_b/W ratio ranged from 8% for flexible high-rise RC buildings to 15% for

rigid low-rise masonry buildings; these values were derived for the highest seismic intensity (IX) and medium soil conditions.

The 1964 code contained basic seismic detailing provisions for masonry and RC structures. The following three lateral load-resisting systems were permitted for RC buildings: frame, structural wall, and dual frame-wall system. Basic requirements regarding the detailing of reinforcement in RC beams and columns were included in the code, e.g., anchorage length and lap splice details. Reduced tie spacing was prescribed within column and beam end zones; however, 135-degree hooks for stirrups and ties were not required. It should be noted that both mild and ribbed steel reinforcement were used until the late 2000's, thereafter only ribbed reinforcement was allowed. No specific detailing requirements were prescribed for RC structural walls.

The code prescribed provisions for RC confining elements and rigid floors in masonry buildings. The height restrictions were set for masonry buildings with horizontal RC confining elements (belts), depending on the seismic intensity (which was specified by the seismic hazard map). Up to 3-storey high buildings were permitted at sites with intensity IX, and up to 5-storey buildings for sites with intensity VII. Building height for fully confined masonry buildings (with horizontal RC belts and vertical tie-columns) was restricted up to 5 storeys for sites with intensity IX, and up to 6 storeys for intensities VII and VIII. The thickness of load-bearing walls in masonry buildings typically ranged from 25 to 51 cm.

A subsequent version of the code (PTN-S 1981) was issued in 1981, 2 years after the 1979 Montenegro Earthquake. The PTN-S code was significantly more advanced compared to the 1964 code and was comparable to other international seismic design codes available at the time (Fajfar 2018). A detailed overview of the code was presented by Jurukovski and Gavrilovic (1994).

The equivalent static analysis was permitted for large majority of structures; however, dynamic analysis was required for special structures, e.g., tall buildings more than 25 storeys high, and irregular structures, e.g., buildings with a flexible ground floor. A coefficient accounting for the type of the structural system and estimated ductility (translated to the force reduction factor) was introduced for the first time. For example, V_b/W ratio for a site with the highest seismic intensity (IX) and medium soil category ranged from 5% for flexible high-rise RC buildings to 13% for rigid low-rise masonry buildings.

The code contained more advanced seismic detailing provisions for masonry and RC structures compared to the PTP-12 code from 1964. For the first time, provisions for the design and detailing of ductile RC frames were introduced in the code, including the “Weak beam-strong column” failure mechanism in which plastic hinges are formed at the beam ends. It should be noted that such provisions were descriptive, without specific guidelines. It was recommended to use lightweight infill materials in RC frame systems. When infills were expected to influence the frame behavior it was required to provide horizontal reinforcement at the infill-to-column connections; however, this code provision is rarely implemented in practice. Provisions related to the detailing of RC structural walls were included in the code, with specific requirements for distributed horizontal and vertical reinforcement and boundary elements.

Prescriptive provisions were provided regarding the maximum wall spacing, and the size of openings in masonry walls. The thickness of load-bearing masonry walls ranged from 19 to 38 cm, and different masonry units were permitted, including solid clay bricks, modular (multi-perforated) clay blocks, etc. Specific provisions were included regarding the mechanical properties of masonry and the verification of stresses in masonry walls. Building height for fully confined masonry buildings was restricted up to 3 storeys for intensity IX, up to 4 storeys for intensity VIII, and 5 storeys for intensity VII. Up to 3- and

2-storey high unreinforced masonry (URM) structures with horizontal RC belts were permitted for sites in intensity zones VII and VIII respectively but were not permitted for intensity zone IX. A detailed overview of seismic design and detailing requirements for masonry buildings in Serbia was presented by Blagojević et al. (2021).

Eurocodes were officially adopted as governing codes for the design of building structures in Serbia in 2019 (PGK 2019). Currently, Eurocode 8—Part 1 (EN 1998-1:2004, 2004) is enforced for the seismic design of new structures in Serbia (SRPS EN 1998-1/NA:2018 2018).

2.3 Evolution of seismic maps and seismic hazard parameters

Seismic hazard maps for Serbia evolved since 1950, when the first seismic zoning map was compiled in Yugoslavia based on the largest observed macro-seismic intensities. The map was used in conjunction with the 1964 seismic design code (PTP-12 1964). In 1982, a temporary seismic zoning map was issued for the design according to the 1981 code (PTN-S 1981). Subsequently, the map was updated in 1987 based on the largest intensities observed at the time. Six new seismic zoning maps were created based on the probabilistic seismic hazard assessment (PSHA) approach, for the return periods of 50, 100, 200, 500, 1000, and 10,000 years. In 1990, a map for the 500-year return period was included in the 1981 code (Official Gazette of SFRY 1990). Although the map was developed based on a PSHA approach, the seismic hazard was still expressed through the macro-seismic intensity degrees and for the average ground conditions. Values from the 1990 seismic hazard map were used for the design of class II and III buildings according to PTN-S, i.e., residential buildings, hotels, restaurants, etc.

In 2018, new seismic hazard maps were issued by the Seismological Survey of Serbia (SSS 2018) for seismic design in compliance with Eurocode 8 (EN 1998-1:2004 2004). The maps were compiled based on the PSHA approach, with the seismic hazard defined by PGA values for the 95-year return period earthquake (“damage limitation” requirement), and the 475-year return period earthquake (“no-collapse” requirement), see Fig. 2. Both maps show PGA values for the ground type A, defined by the code as the “rock or similar geological formations (including at most 5 m of a weaker material at the surface), with the average shear wave velocity in the top 30 m greater than 800 m/s”. The PGA value is to be multiplied by an appropriate value of soil factor, S , which depends on the spectrum type (1 or 2) and ground type (A to E).

Table 1 shows macro-seismic intensity degrees for the two largest cities in Serbia, Belgrade and Novi Sad, as given in the 1950, 1982, and 1990 seismic zoning maps. Table 1 also presents the horizontal PGA values calculated using the empirical relationship developed for Yugoslavia (Trifunac et al. 1991):

$$\log_{10}(\text{PGA}) = -0.079 + \text{Int} \times 0.290 \pm P \times \sigma; \sigma = 0.049 \quad (1)$$

where PGA (expressed in cm/sec^2) is in the horizontal direction, Int (expressed in $^{\circ}\text{MCS}$) is the macro-seismic intensity degree, σ is the standard deviation, P is 0 for the median estimate and ± 1 for \pm one standard deviation.

Table 1 displays the median empirical PGA estimates for the two cities and shows the macro-seismic intensities and PGA values from the maps for the 95 and 475-year return periods, as proposed in 2018 by the Seismological Survey of Serbia (SSS 2018). For each city, both the PGA value for rock sites and the value multiplied by the largest soil factor ($S = 1.4$) for Type 1 spectra and ground type E are presented (EN 1998-1:2004 2004).

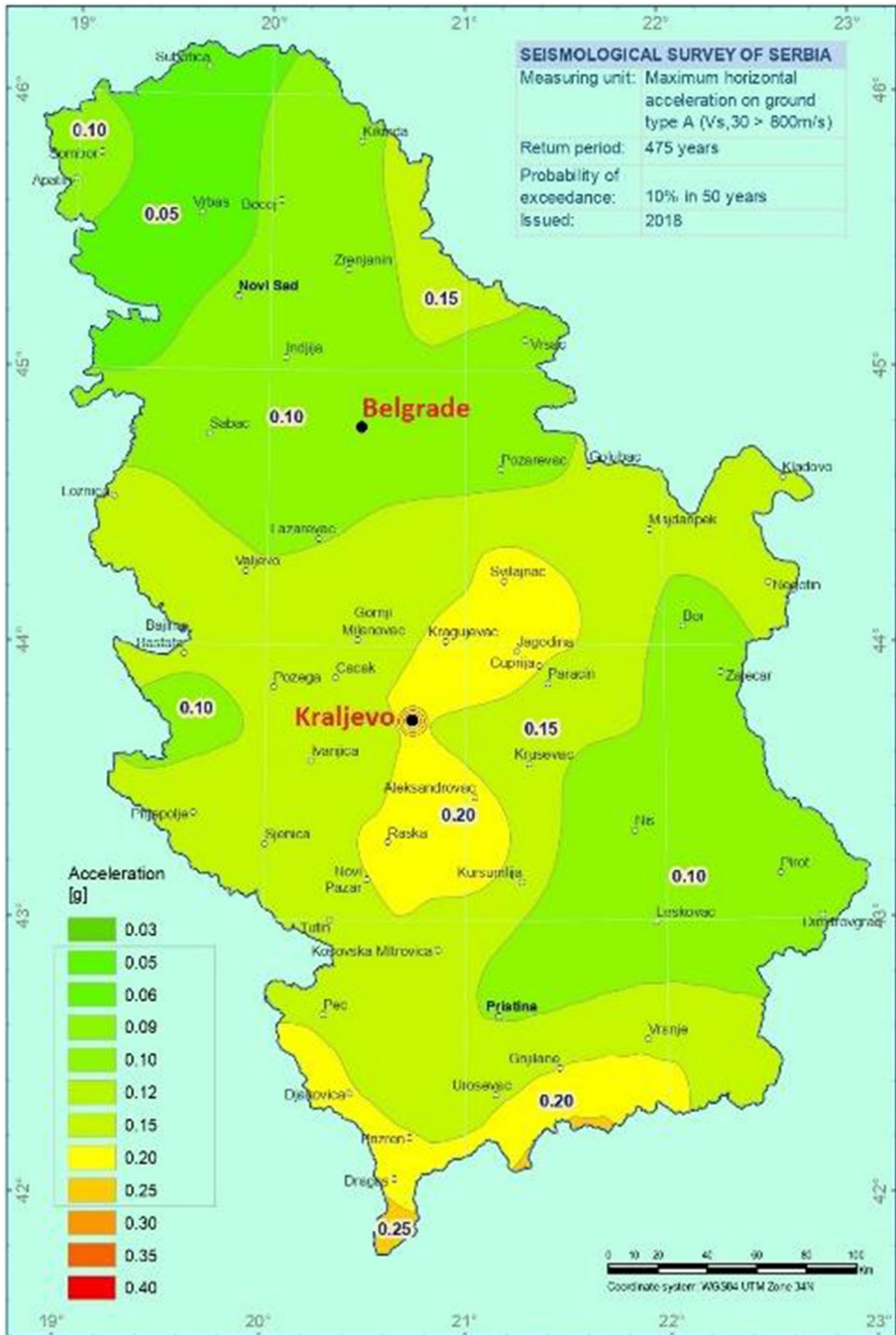


Fig. 2 Seismic hazard map for Serbia showing the PGA values for an earthquake with a 10% probability of exceedance in 50 years according to the Eurocode 8 requirements (SSS 2018)

Table 1 The equivalent empirical horizontal PGA estimates for the two most populated Serbian cities based on the intensities specified in the official seismic zoning maps

City	Year of the seismic map												
	1950		1982		1990		2018		2018				
	50 yrs	100 yrs	200 yrs	500 yrs	1000 yrs	10,000 yrs	95 yrs	95 yrs	475 yrs	475 yrs			
Belgrade (Beograd)	I [°MCS]	VII	VII	VII	VIII	VIII	VIII	IX	IX	IX	VI-VII	VI-VII	VII-VIII
	PGA [g]	0.09	0.09	0.18	0.18	0.35	0.35	0.350	0.350	0.350	0.06-0.08	0.06-0.08	0.10-0.14
Novi Sad	I [°MCS]	VI	VII-VIII	VIII	VIII	VIII	VIII	VIII-IX	VIII	VIII-IX	VI	VI	VII-VIII
	PGA [g]	0.05	0.09-0.18	0.18	0.18	0.18	0.18	0.18-0.35	0.18	0.18-0.35	0.03-0.04	0.03-0.04	0.10-0.14

Since the combined population of Belgrade and Novi Sad amounts to nearly 30% of the total population of the country, the respective seismic hazard estimates are expected to significantly affect the total estimated seismic risk for Serbia. It can be seen from Table 1 that for the 475-year return period earthquake the PGA values from the 2018 seismic hazard maps are up to 44% less than the values derived from the seismic intensities from the 1990 hazard maps (for the 500-year return period).

The significance of the vertical strong motion component should also be mentioned as it reduces the compressive capacity of the structural elements. Bulajic et al. (2021, 2022) have recently studied vertical seismic components for the case-study region of Osijek, Croatia, based on the available regional strong motion data. These studies have demonstrated that the Eurocode 8 can underestimate the vertical to horizontal spectral ratios for Type 2 spectra by a factor of three while at the same time overestimating these ratios for Type 1 spectra by a factor of two.

3 Republic of Serbia: History, population and building stock

3.1 Historical context

Construction practice and architectural planning of residential buildings in Serbia were influenced by the political, economic, and social context characteristic of different periods. The relevant historic periods are (i) the Ottoman Empire (from 1459 until 1815); (ii) the transition period during the Principality of Serbia until World War I (1816–1918); (iii) the Kingdom of Yugoslavia (1919–1940); (iv) World War II (1941–1945); (v) post-war recovery (1946–1963); (vi) construction boom (1964–1980); (vii) reduced investments and construction activities (1981–1991), and (viii) post-Yugoslavia period (1992–present), which was characterized by reduced investments and a lower level of regulation and code enforcement related to building construction compared to previous periods.

Serbia and other Western Balkan countries were a part of the Ottoman Empire from the 15th to 19th century. Construction practice during that period was significantly influenced by the Ottomans. Massive earthen wall structures and traditional buildings featuring Ottoman-style timber frame structures with earthen or brick masonry infills were widely used for the construction of public and residential buildings. However, after the Second Serbian Uprising in 1815, the Principality of Serbia evolved from an authoritative towards a more democratic society. The transition period, until the beginning of World War I (WWI) in 1914, was characterized by the development of local facilities for manufacturing building materials and artisan workshops which produced architectural and decorative elements. As Serbs were fighting for independence from the Ottomans, there was an effort to break away from the oriental traditions and adopt the culture and traditions of Central Europe in all spheres of life, including architecture and construction practices. During that period, traditional timber-framed construction was still used, but brick masonry infills became thicker and more robust over time. A complete transition to brick masonry construction took place in the second half of the nineteenth century. It was reported that a few brick manufacturing facilities were established around the 1880s (Radivojević et al. 2016).

Several important public buildings, including hospitals, educational and cultural institutions were constructed during that period. European-style masonry buildings became

prominent in the centre of Belgrade after the 1870s. They reflected the principles of architectural planning and design, as well as construction practices characteristic of Central Europe. The first reported application of RC technology in Serbia was in the National Museum building in Belgrade, which was originally constructed as the National Treasury in 1903. Vertical structural elements were massive URM walls, but the floor system consisted of 10 cm thick RC slab segments spanning between the iron beams (Stojanović 2019).

During the period from 1918 to 1941, that is, until the beginning of World War II (WWII), massive brick masonry was the prevalent wall construction practice. Ribbed RC floors were used for the construction of residential and public buildings, while wooden floors were commonly used for the construction of single-family dwellings. During WWII Serbia and other Western Balkan countries suffered severe destruction. Many buildings were destroyed in bombing raids. It is expected that, if any, construction activities were undertaken only for military purposes.

After WWII Serbia was a part of the Socialist Federal Republic of Yugoslavia (SFRY) (referred to as Yugoslavia in this paper) from 1945 to 1991. The initial period (1945–1963) was characterised by post-war rebuilding and recovery. There was a significant need for mass housing construction to accommodate the population's needs. The majority of urban buildings from that period are mid-rise URM structures. Most buildings in larger cities were 4–6 storeys high, while low-rise buildings (up to 3-storey high) were prevalent in smaller towns and rural areas. Large-scale application of RC construction started in the 1950s, with the first applications of prefabricated concrete construction technology for housing.

The period from 1964 to 1980 was characterised by a construction boom. The first seismic design code of Yugoslavia was released in 1964, and RC technology was widely used both for prefabricated and cast-in-situ construction. Several proprietary prefabricated concrete systems were used for housing construction in urban areas. Cast-in-situ RC buildings were mostly in the form of moment-resisting frames with masonry infills, however RC structural walls were provided in taller buildings. Buildings in urban areas were larger in size and were usually 4–7 storeys high, except for free-standing high-rise buildings (towers) which were usually taller than 10 storeys. Load-bearing masonry continued to be a prevalent form of construction for low-rise buildings in urban and rural areas. Masonry walls were reinforced with horizontal and vertical RC confining elements (confined masonry). During that period solid clay bricks were slowly replaced by modular (multi-perforated) clay blocks (this transition started in the 1960s).

After 1981, construction practices were similar to those characteristic of the previous period, but the scale of construction activities was much smaller due to reduced investments. It should be noted that prefabricated concrete technologies were no longer practised after the breakdown of Yugoslavia in 1991. Due to the economic challenges and civil war in the 1990s, construction activity (both in public and private sectors) was limited. Many existing buildings were renovated during that period, with vertical extensions constructed atop the existing buildings, which in many cases significantly increased their seismic vulnerability. From 2000 to date, the scale of construction activities has somewhat increased compared to the previous period. Cast-in-situ RC construction has been used for mid- and high-rise urban construction, while load-bearing masonry with horizontal and vertical RC confining elements was used for low-rise construction both in urban and rural areas.

3.2 Population and building stock: Census data

The statistical data for the Republic of Serbia is contained in the 2011 Census of population, household and housing units (SORS 2011) (referred to as the Census in the following text). The country has been divided into 25 districts (excluding Kosovo and Metohija). Note that data related to the Autonomous Province Kosovo and Metohija was not included in the 2011 Census. For the purpose of this study, the districts were grouped into the following 6 geographic and administrative regions: the City of Belgrade, Vojvodina (Autonomous Province), West Serbia, Central Serbia, South Serbia, and Southeast Serbia (Fig. 3). The total area of the 6 regions is 77,474 km². According to the 2011 Census, the population of Serbia was 7,186,862 and the total number of housing units was 3,231,931.



Fig. 3 Geographic regions of Serbia (SORS 2011)

Settlements in Serbia can be classified into rural and urban. Rural settlements have low population density, and the population is predominantly engaged in agricultural activities. Although rural areas cover 85% of the territory of the Republic of Serbia, most of the Serbia's population (59.4%) occupies urban settlements (Gajić et al. 2021; SORS 2011), see Fig. 4. SORS (2011) differentiates between “urban” and “other” settlement types. For this study, the category “other” will be referred to as “rural”.

The three largest cities in Serbia are the City of Belgrade (population 1,659,440), Novi Sad (population 341,625), and Niš (population 260,237) (SORS 2011). A review of the region-wise distribution of the population and housing has shown that approximately 50% of the total population resides in the City of Belgrade (approx. 23%) and Vojvodina (approx. 27%), Fig. 4. According to the Census, the building stock of Belgrade is predominantly urban (81%). Similarly, majority of the building stock in Vojvodina is urban (approx. 59%), but in other regions of the country urban and rural building stock are more equally distributed (Fig. 5). It should be noted that rural dwellings can be found in the suburbs of Belgrade and are mostly constructed in an informal manner. For example, suburban settlement Kaluđerica, with a population of 26,904 according

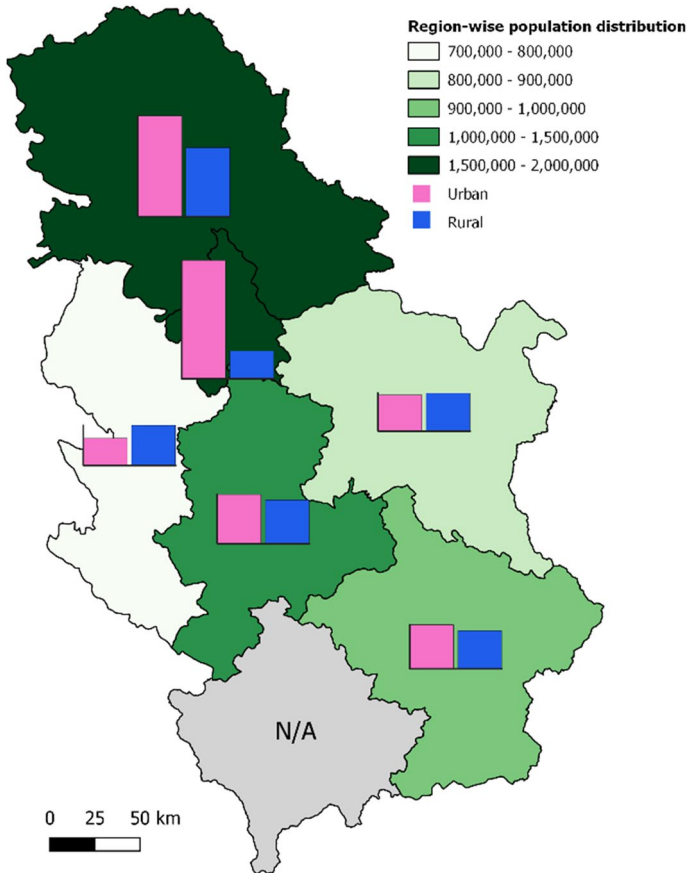


Fig. 4 Region-wise distribution of population (different colours) and the corresponding ratios of urban and rural population (column charts)

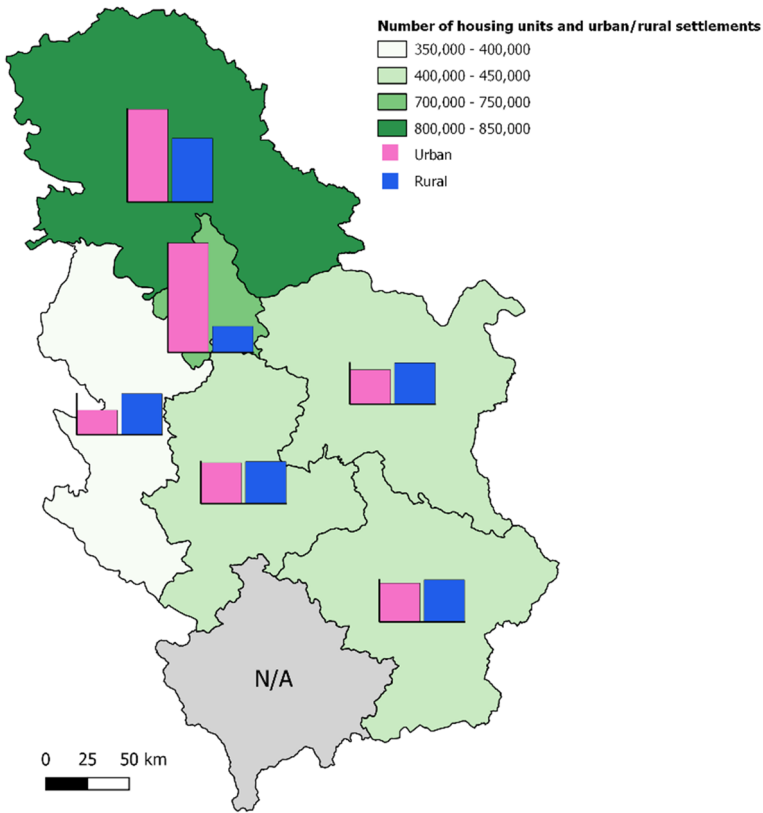


Fig. 5 Region-wise distribution of housing units (different colours) and the corresponding ratios of housing units in urban and rural settlements

to SORS (2011), is considered the largest informal settlement in Europe (Simeunčević Radulović et al. 2013).

The Census confirmed that a major fraction of the building stock in Serbia is residential. The number of housing units corresponds to the number of habitation spaces with a single household, e.g., apartments, which have one or more rooms with/without auxiliary facilities, e.g., kitchen, pantry, hall, bathroom, toilet, etc. The Census differentiates between housing units located in residential buildings with one, two, three and more housing units. In addition, there are housing units in “other residential buildings”, and also in non-residential buildings (where less than 50% of total useful floor space is for residential use). It should be noted that housing units in “other residential buildings” and non-residential buildings were disregarded in this study because they account to only 0.3% of the residential building stock.

Figure 6 presents a region-wise distribution of housing units, as well as a distribution of housing units depending on the building size (one, two, three and more housing units). In the national capital, Belgrade, the majority of housing units (66%) are located in residential buildings with three and more housing units (multi-family residential buildings). In contrast, in the remaining five regions of Serbia more than 70% of housing units are located in buildings with a single housing unit (single-family dwellings). Information related to

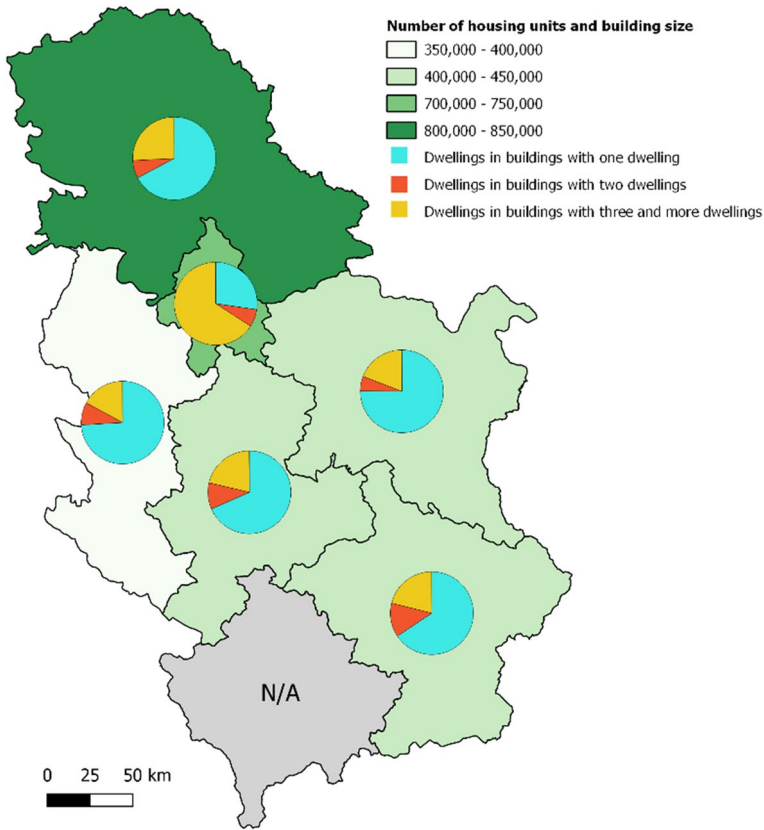


Fig. 6 Region-wise distribution of housing units (different colours) and the corresponding ratios of housing units based on the building size (one, two, three and more housing units) (pie-charts)

number of housing units per building is very important for development of exposure models for seismic risk studies, because it can be used to estimate the building height and number of buildings.

The Census also contains statistical data related to the year of construction, and region-wise information is presented in Fig. 7. The following periods (range of years) were considered in this study: before 1945; 1946–1960; 1961–1980; 1981–2011 (year of the last Census); and unknown year. Approximately 10% of all housing units were constructed before 1945; however, housing units in buildings of pre-1945 vintage constitute a more significant fraction of the residential building stock in Vojvodina compared to other regions (approx. 17%).

Majority of housing units in Serbia (63%) are situated in the residential buildings constructed between 1945 (end of World War II) and 1990. It is estimated that around 37% of all housing units in Serbia were constructed between 1971 and 1990, which can be attributed to a major upswing in the construction sector, both in terms of single-family dwellings (buildings with one or two housing units) and multi-family residential buildings, mostly in the form of apartment blocks constructed using prefabricated construction technology (buildings with three and more housing units).

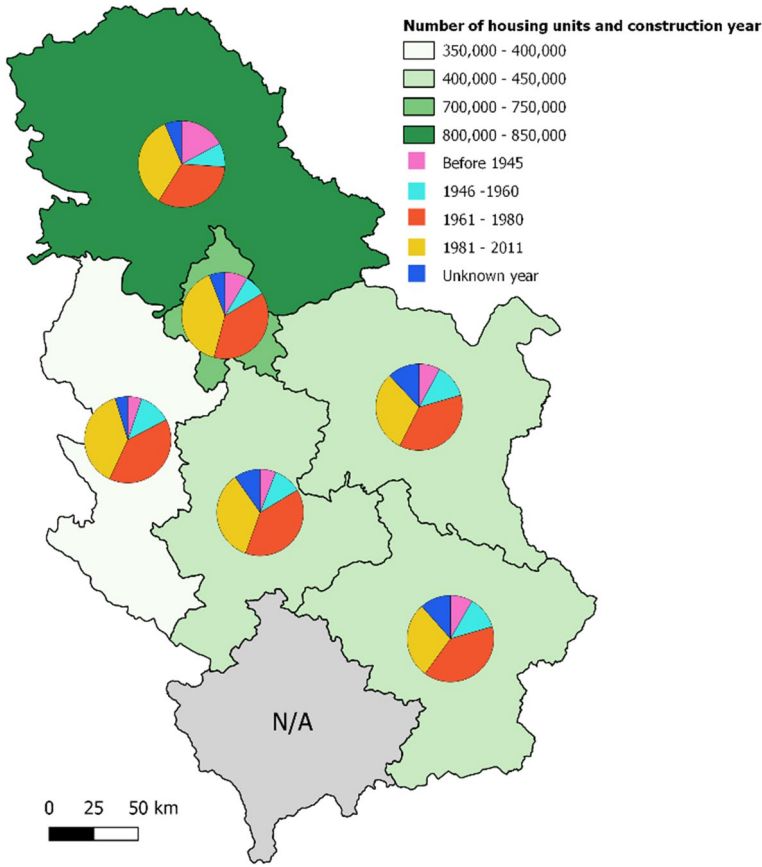


Fig. 7 Region-wise distribution of housing units (different colours) and the corresponding ratios of housing units based on the year of construction (pie-charts)

3.3 Previous research studies related to the building stock in Serbia

Previous research studies on the Serbian building stock were mostly related to international projects which were primarily based on the analysis of the building stock of various European countries. The most relevant project for this study is the TABULA project (2009–2012), a European project co-founded by Intelligent Energy Europe (Jovanović Popović et al. 2013a). In the framework of the TABULA project, a detailed analysis of residential building typologies was performed based on the construction period, façade systems and energy consumption. Two taxonomies were developed for each country: the TABULA taxonomy and a national taxonomy. Both taxonomies classified buildings based on the year of construction and the taxonomy-specific building type. The TABULA taxonomy divided buildings into four types: single-family houses, terraced houses, multi-family houses and apartment blocks. The national building taxonomy for Serbia is more complex, and it categorises the buildings into six types (Jovanović Popović et al. 2013a). Single-family housing was classified into freestanding houses and houses in a row, while multi-family housing was categorised into freestanding buildings, lamelas (housing blocks), buildings

in a row, and high-rise buildings. Figure 8 shows a summary of the national taxonomy for Serbia and features representative buildings for each typology and construction periods. Each typology was described in detail on an example (building archetype) and includes a description of the structural system and horizontal and vertical structural elements. The TABULA project also offered an insight into the type, built-up area, and number of residential buildings for various typologies in Serbia, based on the 2011 Census data, as well as a detailed survey of 10,000 buildings. It was shown that most buildings in Serbia are freestanding single-family houses (57.0% based on the built-up area and 92.1% based on the number of buildings). Also, it was concluded that most freestanding single-family houses were built between 1971 and 1980. The TABULA project deliverables prepared by














































	породично становање (до 4 стана) family housing (up to 4 apartments)			вишепородично становање (више од 4 стана по улазу) multifamily housing (more than 4 apartments per entrance)		
Тип	1  слободностојећа Freestanding	2  у низу In a row	3  слободностојећа Freestanding	4  ламела Lamela	5  у низу In a row	6  солитер High-rise
А < 1919.						
Б 1919–1945						
Ц 1946–1960						
Д 1961–1970						
Е 1971–1980						
Ф 1981–1990						
Г 1991–2011						

Fig. 8 Residential building taxonomy for Serbia developed for the TABULA project—the columns show building typologies, and the rows show different construction periods (Jovanović Popović et al. 2013a)

the Serbian team (Jovanović Popović et al. 2013a) were important resources for the present study.

The ENTRANZE project (2012–2014), although focused on energy efficiency in European buildings, also included useful information regarding the Serbian building stock (Mariottini 2013). The building stock was classified based on the floor area: residential buildings account for 164 million m² or 83% of the total floor area of all buildings in Serbia. The majority of housing units (53%) are located in single-family houses while the remaining 47% housing units are located in multi-family residential buildings.

Within the framework of the EU's Horizon 2020 project Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe (SERA), the European seismic risk model was developed (Crowley et al. 2021). Researchers from various countries contributed information related to the building stock relevant for the exposure model. Information related to the Serbian building stock was provided by members of the Serbian Association for Earthquake Engineering (SUZI-SAEE). An initial building classification for Serbia was presented at the SERA workshop in 2019 (Borozan 2019).

4 Classification of residential buildings in Serbia

4.1 An overview of relevant global and regional building taxonomies

Building taxonomy, also known as a building classification system, is fundamental for seismic risk assessment studies and is used to classify a building or a building portfolio through a set of attributes (facets), which could influence both the likelihood and extent of earthquake-induced damage. This subsection presents a brief overview of relevant taxonomies which have been considered in this study.

Most of the existing building taxonomies have a regional scope, while only a few taxonomies address the global building stock. The most detailed global taxonomy was developed for the Global Earthquake Model (GEM) and is known as the GEM Building Taxonomy V2.0 (Brzev et al. 2013). The taxonomy characterizes buildings through 13 attributes, including Lateral Load Resisting System (LLRS), material of the LLRS, building height, date of construction, type of occupancy, type of floor and roof, structural irregularity, etc. The taxonomy has been widely used for natural hazard and risk assessment via the Open Quake platform (Silva et al. 2014) and has been expanded into the GED4ALL Building Taxonomy, which includes additional attributes and details required for multi-hazard risk assessment studies (Silva et al. 2022). GEM Building Taxonomy V2.0 has also been used in the European seismic risk model developed in the framework of SERA project (Crowley et al. 2021). PAGER-STR is another comprehensive, but hierarchical global building taxonomy, which classifies buildings into 101 classes, based on the material of LLRS, type of LLRS, building height, and type of diaphragm (in some cases) (Jaiswal and Wald 2008). World Housing Encyclopedia (WHE) is an ongoing international initiative focused on mitigating seismic risk associated with residential buildings in various countries and regions (EERI 2022). WHE is an online repository of relevant resources, including housing reports which present an overview of different building typologies, and include architectural, structural/seismic and other features of housing construction from more than 45 countries.

Several building taxonomies have been developed in Europe. According to the EMS-98 Macroseismic Scale (Grünthal 1998) buildings have been classified into 15

classes, including 7 masonry, 6 RC, steel, and timber building classes. Each building class has been assigned an expected seismic vulnerability rating. The level of seismic design has been considered only in the context of RC structures. In the framework of the RISK-UE project, a building taxonomy was proposed for seven European cities. Buildings were classified into 23 classes depending on the LLRS, material of construction, building height, and building design code level (Mouroux et al. 2004; Milutinović and Trendafiloski 2003). Finally, the Syner-G taxonomy was specifically developed for classifying the European building stock. It includes 15 main attributes/facets and can be used to classify buildings in a flexible (non-hierarchical) manner (Pitilakis et al. 2014).

Building taxonomies developed in former Yugoslavia and taxonomies developed in neighbouring countries were also reviewed at the onset of this study. An official building classification was not in place in Yugoslavia. However, an earthquake damage inspection form which was developed in the 1980s as a part of the UNIDO project “Building Construction under Seismic Conditions in Balkan Region” (UNIDO 1985) provided a simple building classification system. The form contained a classification based on the construction material (e.g., masonry, RC), construction technology (e.g., cast-in-situ or prefabricated) and the structural system (e.g., wall, frame, frame-wall system, etc.). This form was used for damage assessment after the December 21, 1990, Griva (Gevgelija) earthquake in North Macedonia (IZIIS 1991).

In Croatia, the Long-Term Strategy for Encouraging Investments in the Restoration of the National Building Stock provided an overview of the national building stock, based on the census data and expert estimates (Pavić et al. 2020a). A taxonomy of buildings for the City of Osijek included 15 prevailing building typologies, and was developed based on a field survey of the building stock for exposure model development purposes (Pavić et al. 2020b). In the last few years, several studies were focused on developing a taxonomy for the building stock in the country’s capital Zagreb. The initial taxonomy comprised of 14 characteristic building typologies (Šavor Novak et al. 2018); however, further studies indicated a need for a classification that more precisely reflects the building characteristics, hence a more detailed taxonomy which included 42 building typologies was created. An overview of numerous methodologically different risk assessment studies for Zagreb was presented by Atalić et al. (2019).

Bosnia and Herzegovina (B&H) currently lacks a well-organized and efficient database of building typologies. Recent seismic risk assessment studies in the B&H were focused on masonry buildings, including URM buildings with flexible floors, URM buildings with rigid floors, and confined masonry buildings (Ademović et al. 2022).

According to the authors’ best knowledge, the only previous study related to Serbian building stock classification for seismic risk assessment purposes was reported by Radovanović and Petronijević (2009). The authors applied the EMS-98 scale (Grünthal 1998) to identify common building typologies in Serbia and concluded that seven EMS-98 typologies, that is, 5 masonry typologies (M2, M4, M5, M6 and M7) and two RC typologies (RC1 and RC4), can be used to characterise residential building stock in Serbia. A review of previous studies on the residential building stock has revealed a need to develop a novel building classification system focused on the residential building stock, which is presented in the following section. The proposed classification can be mapped to the typologies contained in the EMS-98.

4.2 The proposed taxonomy of residential buildings in Serbia

The proposed taxonomy of residential buildings in Serbia, as presented in this subsection, has been developed based on earlier studies on Serbia's building stock, international building taxonomies, and the authors' experience. The classification is presented in Table 2 and includes an alphanumeric ID for each building typology (M1, RC2, etc.), name, and details related to the primary and secondary taxonomy attributes. The primary attributes are explicitly included in the typology name, while secondary attributes have been assigned based on the information from the literature.

The attributes considered in this classification are deemed relevant for making a distinction between different building typologies in terms of their seismic vulnerability, which is critical for seismic risk studies. The proposed building classification includes the following attributes: Lateral Load-Resisting System (LLRS), e.g., wall, frame, dual wall-frame system, and material of the LLRS (e.g., masonry, RC, wood). The type of floor diaphragm (rigid or flexible) has been specified only for masonry typologies M1, M2, and M3, which are characterized by URM walls. URM buildings with flexible diaphragms (building types M1, M2) are more vulnerable to earthquake shaking than similar URM buildings with rigid diaphragms, as demonstrated by numerous surveys and studies (Kim and White 2004). Buildings with flexible diaphragms commonly experience large lateral displacements and the out-of-plane toppling of the walls, which negatively impacts building integrity and prevents the walls from acting together as a box (box action). Excessive lateral displacements of flexible floor diaphragms have caused damage or failure of gable walls which are common in older URM buildings in Serbia, Croatia, and other neighbouring countries. Furthermore, the M3 type (URM walls with rigid diaphragms) has been further classified into single-family and multi-family building types, hence building height has been identified as an additional attribute for this typology. It should be noted that the term "storey" in the context of building height is different than "floor". The latter term is used in the context of number of floor/roof levels. For example, a single-storey building in Serbia has ground floor and first floor, that is, two floor levels.

A review of past studies was useful for establishing types of LLRS and the predominant material of LLRS. Following a review of previous studies and the authors' experience, the proposed building classification considers 9 building typologies. Out of those, 5 are related to masonry structures (M1 to M4), 3 are related to RC structures (RC1 to RC3), and one is related to wood structures (W). Four out of five masonry typologies (M1, M2, M3-S and M3-M) are related to URM construction, while M4 is related to confined masonry. Out of three typologies related to RC structures, two are related to buildings constructed using cast-in-situ concrete technology (RC1 and RC2), while the third one is related to prefabricated RC buildings (RC3). Wooden buildings (W) constitute a small fraction of the residential building stock, however existing buildings of that type are still being occupied in rural areas of the country. Since the paper is focused solely on residential buildings, steel building typologies are not considered since they are mostly found in industrial and commercial facilities in Serbia.

Besides the three primary attributes (type and material of LLRS and type of floor diaphragm), building height and year of construction (or approximate period) are also considered to be fundamental for seismic risk assessment studies, and have therefore been identified as secondary attributes. Building height can be used to determine the dynamic characteristics of a structure (such as fundamental period), while the year of construction can be linked to the seismic design code and corresponding provisions

Table 2 Proposed taxonomy of residential buildings in Serbia

ID	Building typology	Primary attributes		Secondary attributes
		Material	LLRS	
(1) W	Wooden frames with infills	(3) Wood	(4) Wall—constructed in the form of a wooden frame braced either with thatch infill and covered by mud mortar (<i>bondruk</i>), or with unburnt clay brick infill (<i>ćerpić</i>); alternatively, the walls are built using woven brushwood infilled with clay (<i>čatmara</i>)	(6) <i>Height:</i> 1–2 floors <i>Date of construction:</i> before 1945
M1	Unreinforced earthen or stone masonry walls with flexible diaphragms	Masonry	Wall -constructed using stone masonry (rubble stone, partially dressed stone), rammed earth (<i>naboj</i>), or load-bearing adobe brick masonry	<i>Height:</i> 1–2 floors <i>Date of construction:</i> before 1945
M2	Unreinforced masonry walls with flexible diaphragms		Wall—constructed using solid clay bricks in low-strength mortar (lime:sand)	<i>Height:</i> 1–4 floors <i>Date of construction:</i> before 1960
M3	Unreinforced masonry walls with rigid diaphragms		M3-S (single-family) Wall - constructed using modular (multi-perforated) clay blocks in cement-based mortar M3-M (multi-family) Wall - constructed using solid clay bricks in cement-based mortar	<i>Height:</i> 1–2 floors <i>Date of construction:</i> 1950-present
M4	Confined masonry buildings		Wall - constructed using modular (multi-perforated) clay blocks in cement-based mortar	<i>Height:</i> 1–5 floors <i>Date of construction:</i> 1970-present

Table 2 (continued)

ID	Building typology	Primary attributes		Secondary attributes
		Material	LLRS	
RC1	RC frames (cast in-situ) with masonry infills	Reinforced concrete (RC)	RC frame with masonry infills built using solid clay bricks or modular clay blocks	Type of roof/floor diaphragm Rigid (semi-prefabricated RC or composite concrete and clay floor system) <i>Height:</i> 4–10 floors <i>Date of construction:</i> 1960–present
RC2	RC walls (cast in-situ) or dual frame-wall system		Wall (although a frame may resist a small fraction of seismic load)	<i>Height:</i> 5–15 floors <i>Date of construction:</i> 1960–present
RC3	Prefabricated RC buildings		Wall (large panel buildings), or dual frame-wall system	<i>Height:</i> 6–15 floors <i>Date of construction:</i> 1960–1990

which may significantly influence the seismic performance. Information related to these two attributes is not available in the Census and needs to be inferred.

4.3 Residential building typologies in Serbia: key features

This subsection presents relevant features of prevalent residential building typologies in Serbia according to the proposed classification system presented in Table 2.

4.3.1 W: Wooden frames with infills

Until the twentieth century wood was extensively used as a building material for residential construction in Serbia. By and large, wooden buildings were low-rise single-family dwellings, and have either one or two floors. The majority of existing wooden buildings in Serbia are examples of timber-framed construction, which was widely practised in Serbia and other countries in the region which were a part of the Ottoman Empire. This vernacular construction practice was common in central, eastern, and southern Serbia. Timber-framed construction was practised in urban and rural areas of the country until the end of the nineteenth century and mid-twentieth century respectively. The structural system is a timber frame consisting of horizontal, vertical and diagonal timber elements with an infill made of lighter materials (Fig. 9). The type of infill depends on the occupant needs and financial constraints, ranging from low-cost materials (thatch and mud) to more expensive materials like adobe bricks. A timber-framed system with infill made either of adobe bricks (*čerpič*) or thatch covered by mud plaster is known as *bondruk* in Serbia. Another type of timber-framed system, *čatmara*, has walls made of woven brushwood (*čatma* in Turkish) and infilled with mud. These buildings have a sloped roof, usually with clay tile roofing (called *čeramida* in Serbian). Apart from the timber-frame construction, wooden log cabins (called *brvnara* or *talpara* in Serbian) were the most dominant type of single-family residential construction in mountainous rural areas of western Serbia (Rodić 2016). Walls are constructed using wooden logs or planks, while foundations and plinths are constructed using stone masonry. Newer buildings of this type have shingle roofing; however, straw or thatch roofing is common in older buildings.

4.3.2 M1: Unreinforced earthen or stone masonry walls with flexible diaphragms

The majority of M1 residential buildings in Serbia were constructed using earthen or adobe masonry walls. Stone masonry has been traditionally used for construction of older public



Fig. 9 Wooden building typology(W)—examples from Serbia: **a** a single-storey timber frame (*bondruk*) house close to Valjevo; **b** a single-storey rural house (*čatmara*) in the Nemenikuće village, and **c** a wood log rural house (*brvnara*), Zlatibor

buildings, fortresses, and religious structures (churches, monasteries); however, older stone masonry houses exist in rural areas of the country.

Earthen construction was practised in Vojvodina (northern part of Serbia) in the 18th, 19th and first half of the 20th century (until the end of WWII). These are low-rise single-family buildings, and typically have only one floor in rural areas and two floors in urban areas. A significant fraction of the existing building stock in Vojvodina was constructed before 1945, using mostly earthen construction (Jovanović Popović et al. 2013b).

Rural dwellings were mostly constructed using rammed earth technology (called *naboj* in Serbian), while adobe (unburnt clay bricks) was used for the construction of urban buildings. The soil in Vojvodina is of excellent quality (loam) and is suitable for constructing rammed-earth walls. Such walls were constructed by placing formwork on both wall faces and compacting earth in 10–20 cm high layers. The walls were reinforced with daub and covered by mud and straw plaster (Bogićević 2009). Wall thickness is usually 50 cm or higher. Dwellings of this type are detached (free-standing) houses in rural areas, while in urban areas they are usually in the form of houses in a row. These buildings usually have a rectangular- or L-shaped plan.

Adobe bricks were used for construction of load-bearing masonry walls in urban buildings in Vojvodina from the eighteenth century until the end of WWII. These buildings are up to two-storey high and have wooden floors. They are usually located in historic urban centres in Vojvodina and have adjacent buildings on one or two sides. A few existing buildings of this type have been recognized as heritage structures in Novi Sad (ZZSKGNS 2014), see Fig. 10a. Buildings with adobe walls reinforced with horizontal wooden bands are present in Kosovo and Metohija, and are similar to vernacular construction practice in Greece and Turkey (Rodić 2016). It is expected that mud mortar was used for wall construction in these buildings. Buildings of this type have sloped wooden roofs covered by clay tiles.

Stone masonry has not been widely used for the construction of single-family residential buildings in Serbia, hence there are very few buildings of this type in the country. However, it was reported that larger residential buildings in Belgrade constructed circa 1870 had stone masonry foundations and basement walls, while both stone and brick masonry were used for the construction of load-bearing walls (Radivojević et al. 2016). A limited number of tower-like dwellings (called *kula* in Serbian) were constructed using stone masonry



Fig. 10 URM buildings with flexible diaphragms: **a** type M1: an URM building with adobe walls constructed at the beginning of the nineteenth century in Dunavska Street 2, Novi Sad and **b** Type M2: an URM house with brick masonry walls constructed in Belgrade in 1884

in rural areas, e.g., near the Dečani Monastery in Kosovo and Metohija. These buildings were constructed in the nineteenth century, as three-storey buildings with wooden floors, a square plan shape, and thick stone masonry walls. There are very few windows in these buildings, which can be attributed to safety concerns.

4.3.3 M2: Unreinforced masonry walls with flexible diaphragms

Masonry buildings of this type were constructed in Serbian urban areas in the nineteenth century and the first half of the twentieth century (before the end of WWII) (Fig. 10b). By and large, these are both single- and multi-family residential buildings with height ranging from 1 to 4 floors. The first brick manufacturing facilities in Serbia were set up in the second half of the nineteenth century; this enabled the use of solid clay bricks (baked bricks) in building construction. Early applications of clay brick masonry were reported in the construction of public buildings and larger residential buildings in urban centers (primarily Belgrade). In 1896, the Building Act for the Town of Belgrade spelt out provisions related to local design and construction practices. The Act limited the use of traditional timber structures and prescribed standard dimensions for clay bricks, which became prevalent wall construction material (Radivojević et al. 2016). Brick dimensions changed over time. Before 1933, when a larger brick size was used, wall thickness ranged from 30 to 60 cm. Usually, exterior walls were 45 to 60 cm thick, while interior walls were 30 cm thick. After 1933, brick dimensions were reduced, hence typical wall thickness was also reduced (ranging from 25 to 51 cm). It is expected that lime mortar was used for brick masonry construction until the end of WWII.

These buildings had wooden floors, consisting of 14 cm×20 cm wooden beams at 80 cm spacing and 2.5 cm thick wooden planks. Flooring consisted of 8 cm thick rammed earth layer supporting a hardwood floor. A vaulted brick floor system, known as jack arch system or Prussian vault (*Pruski svod* in Serbian) was used for the construction of suspended floors above the basement and ground floor levels. The main components of the Prussian vault were shallow brick vaults spanning between the iron beams. Wooden floors were widely used in Serbia until the end of WWI, but were subsequently replaced by ribbed RC floor systems, primarily for building construction in urban areas. The M2-type buildings usually have sloped wooden roofs covered by clay tiles.

4.3.4 M3: Unreinforced masonry walls with rigid diaphragms

The M3 building type is very common both in urban and suburban/rural areas of Serbia and can be classified into subtypes M3-M and M3-S.

Masonry buildings of type M3-M were constructed from the end of WWI until the beginning of the 1970s. These are multi-family apartment buildings found in Serbian urban centres and usually have 3 to 6 floor levels (Fig. 11a). These buildings are regular in plan and elevation, their wall layout is relatively symmetrical, and there are no elevators (only staircases). Load-bearing masonry walls were typically constructed using solid clay bricks and cement:lime:sand mortar. Typical wall thickness is 38–51 cm and 25–30 cm for exterior and interior walls respectively.

Masonry buildings of type M3-S were constructed from the 1950s until the present time. These are low-rise single-family residential buildings found both in suburban areas of urban centres and rural areas (Fig. 11b). Load-bearing masonry walls were typically constructed using modular (multi-perforated) clay blocks or solid clay bricks and

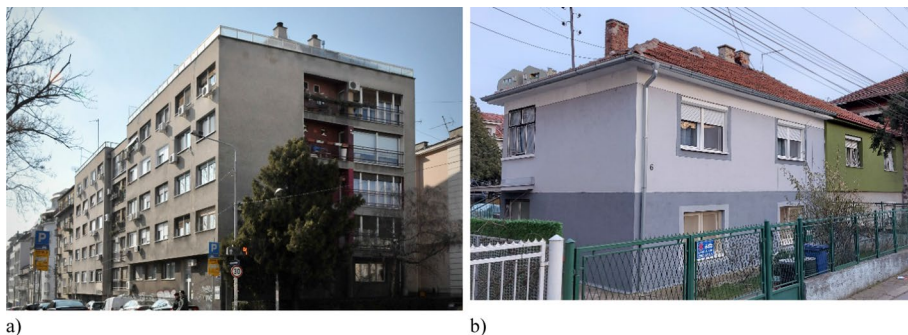


Fig. 11 URM buildings with rigid diaphragms: **a** type M3-M: a typical 5-storey multi-family residential building in Belgrade (post-WWII construction) and **b** type M3-S: a single-family residential building of the 1960 vintage in Niš

cement:lime:sand mortar. Wall thickness ranges from 19 to 38 cm, depending on the building height and the type of masonry unit (clay brick/block).

Floor systems in masonry buildings (types M2, M3, and M4) evolved over time. Initially, ribbed RC floors were used, and the first reported application was in 1909 in a 4-storey residential building in Belgrade (Radivojević et al. 2016). Before the end of WWII, a semi-prefabricated ribbed RC floor system, known as the Herbst system, was practised. It consisted of 25 cm deep prefabricated RC ribs and a cast-in-situ concrete layer. Another semi-prefabricated floor system, called Avramenko, was used since the 1930s. Around the mid-1960s a semi-prefabricated concrete and clay floor system emerged. The system consisted of hollow clay masonry elements which acted as formwork for a ribbed cast-in-situ concrete slab. Variant of this system, called LMT (light prefabricated floor), has been used since the 1980s. It contains cast-in-situ RC joists placed between masonry elements. As an alternative to semi-prefabricated floor systems, solid RC slabs have been used for the construction of multi-storey masonry and RC buildings in the second half of the twentieth century (Đukanović 2021). It should be noted that prefabricated RC hollow core slabs were not used for the construction of floors in masonry buildings in Serbia.

Floor systems in these buildings act as rigid diaphragms under seismic actions. Horizontal RC ring beams were provided at floor and roof levels in the buildings during the period from 1950–1970, however, buildings of earlier vintages did not have RC ring beams, as observed from the results of thermal imaging surveys of sample buildings (Jovanović Popović et al. 2013c). Buildings of this type usually have sloped timber roofs and clay tile roofing. Structural features of M3-type buildings were described in detail in a design case study for Kraljevo, Serbia (Blagojević et al. 2021).

4.3.5 M4: Confined masonry buildings

The M4 buildings have masonry walls reinforced with horizontal and vertical RC elements. Provision of horizontal and vertical RC confining elements in masonry buildings was required by the first seismic design code of Yugoslavia, which was issued in 1964; however, it is believed that wider application of this technology started in the 1970s. These low-rise buildings (usually 1- to 4-storey high) are used both for single- and multi-family residential construction in urban and rural areas of the country (Fig. 12). These buildings

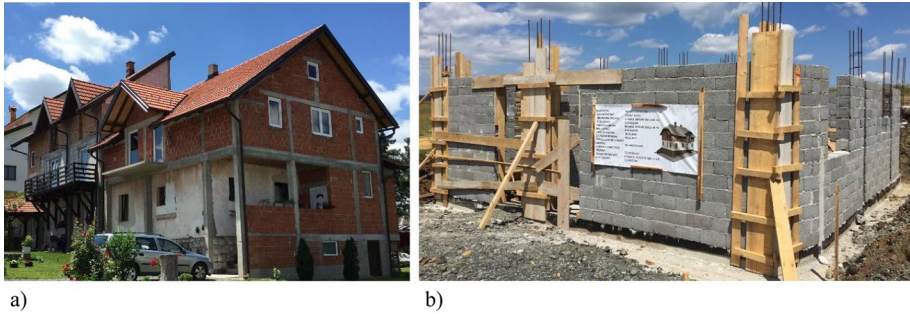


Fig. 12 Confined masonry buildings – type M4: **a** a 2-storey rural house and **b** a rural house under construction, showing formwork for RC confining elements

have masonry walls constructed using modular (multi-perforated) clay blocks, which have been widely used since the 1970s and have replaced solid clay bricks (Đukanović, 2021). Wall thickness ranges from 19 to 25 cm, and a typical mortar composition is a mix of cement, lime, and sand. These buildings have rigid floors, either in the form of cast-in-situ solid RC slabs or semi-prefabricated floor systems (same as M3-type buildings), but the LMT system is also widely used in contemporary construction. These buildings usually have either flat RC roofs (multi-family residential buildings) or sloped wooden roofs (single-family buildings).

4.3.6 RC1: RC frames (cast in-situ) with masonry infills

In the late 1930s, the first RC frame buildings were constructed in Serbia. The structural system was a cast-in-situ RC frame. Despite the knowledge and experience gained in the design and construction of RC structures, residential RC buildings were not common before the end of WWII. The expansion of residential RC frame structures in housing started after WWII, due to extensive industrialization and large-scale population migration to urban areas. Residential RC frame buildings are mostly in the form of mid-rise buildings in a row, with rectangular layouts and commercial areas at the ground floor level. From the end of WWII until the 1970s masonry infills at upper floors were stiff and constructed using solid clay bricks. Since 1970s these infills were constructed using multiperforated clay blocks and precast concrete panels. Ground floor usually has a larger story height and is an open space. The foundations of RC frame residential buildings were strip footings or concrete mats in case of multiple underground levels. The floor system evolved from cast-in-situ ribbed RC floors to cast-in-situ RC flat slabs. It is expected that RC frames constructed before 1964 were designed for gravity loads, without seismic design and detailing considerations. The introduction of the first comprehensive seismic building codes (PTP-12 1964) led to a gradual transformation from the frame, into the dual shear wall-frame system. The code contained basic seismic detailing requirements for RC frame structures, as discussed in Sect. 2.2. Construction of RC frame system for mid-rise residential buildings in urban centres continued until the 1980s when it was replaced by a dual wall-frame system. Furthermore, due to their fast construction and growing market needs, prefabricated RC buildings (type RC3) gradually replaced RC frame buildings constructed in-situ.

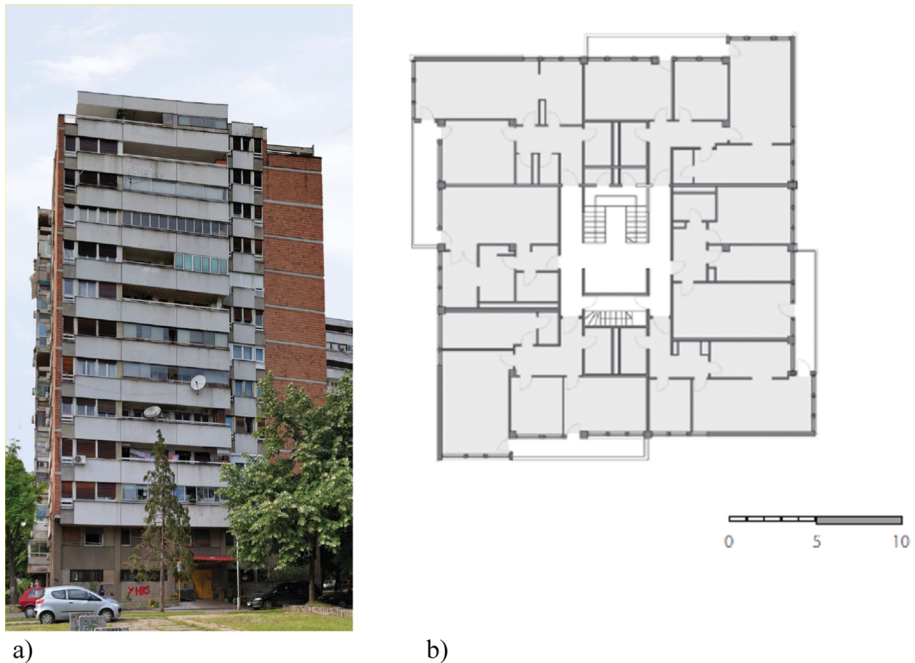


Fig. 13 Cast-in-situ RC frame building typology—type RC1: **a** a 13-storey multi-family residential building in New Belgrade (Block 45) constructed circa 1970 and **b** a typical floor plan (Jovanović Popović and Ignjatović 2011)

Thus, residential cast-in-situ RC frame construction was limited to the historic city cores. An example of a type RC1 building in Belgrade is presented in Fig. 13.

4.3.7 RC2: RC walls (cast in-situ) or dual frame-wall system

The use of RC walls as the lateral load-resisting system began in the 1930s as an additional stiffening of flexible commercial buildings. Construction of RC structural walls in residential buildings started after WWII, and became more widespread around the end of the 1950s, when the slip-form method was applied in the construction of 10-storey plus residential buildings. Due to simplicity and construction speed, the slip-form method was widely used in high-rise residential construction. At the same time, the tunnel-form construction method was introduced for buildings with elongated layouts and heights up to 12 storeys. The buildings had a central core (central corridor in a wide building layout) with walls laid at short and approximately equal spacing and constant thickness over the building height. The floor structure was a typical 16 cm thick flat slab, and a façade was constructed using masonry or precast parapet panels. Tower structures with a central core and exterior columns date from a later period. Wide use of the dual wall-frame system in residential construction started after the 1964 seismic code was issued (PTP-12 1964) and replaced common RC frame structures. The main difference between the RC dual frame-wall system and frame structures was the provision of RC core, and, if necessary, a few additional RC structural walls. The number of dual wall-frame buildings grew over time.

After the 1980s and the discontinued prefabricated construction practice, dual wall-frame system remains the only structural system in use for construction of multi-family residential buildings. In the last decade, there has been a noticeable trend in constructing buildings with RC structural walls and flat slab frames as a gravity load-resisting system. An example of a type RC2 building in Belgrade is presented in Fig. 14.

4.3.8 RC3: Prefabricated RC buildings

The application of prefabricated construction technology in Serbia started in the 1950s and was motivated by the post-WWII housing demand in urban centres of the country. More than 15 different prefabricated systems were used in construction, and many of them were developed in Yugoslavia, e.g., the IMS Building System, Trudbenik, Yugomont YU-61, etc. (Vuković 2007). Many existing prefabricated buildings were constructed using a large panel system, which consists of RC wall and floor panels which were prefabricated in a plant and transported to the construction site, where they were erected in place and joined together. Connections between the structural elements were usually achieved by welding steel plates and bars, followed by grouting using cast-in-situ concrete (so-called “wet connections”). The thickness of wall panels ranged from 16 to 22 cm, while floor panels were approximately 16 cm thick. One of the most popular large panel systems was Rad-Balency, which was originally developed as a French system Balency. The original system was modified to enable high-rise building applications in Belgrade and other major urban centres (Velkov et al. 1984). An example of a 14-storey building in Belgrade constructed using the Rad-Balency system is featured as archetype F7 by Jovanović Popović et al. (2013a). Buildings of this type are mid- to high-rise buildings, with the height usually ranging from 6 to 15 storeys.

Apart from the prefabricated RC large panel system, prefabricated RC frame construction was also used for multi-family residential construction in Serbia’s urban centres. The IMS Building System was developed by Prof. Branko Žeželj at the Institute IMS in Belgrade and consists of prefabricated RC columns, waffle slabs, edge girders and staircases. RC waffle slabs may have a variable span (ranging from 3 to 9 m), but a 4.2 m span was commonly used for residential buildings. The thickness of the floor slab ranged from 22 to

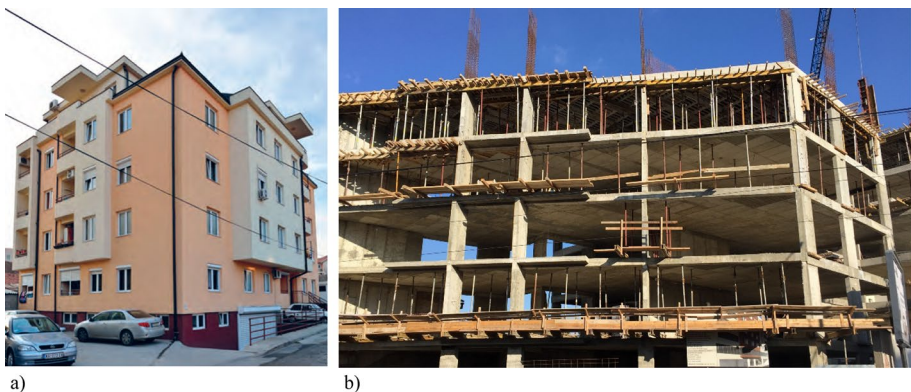


Fig. 14 Cast-in-situ RC frame-wall building typology—type RC2: **a** a 4-storey multi-family residential building in Belgrade (Jovanović Popović et al. 2013c) and **b** an RC2 building under construction in Belgrade

36 cm. Columns were one- to three-storey high, depending on the application, and cross-sectional dimensions may vary from 25 to 60 cm, although 40 cm square columns were most often used. A unique feature of the IMS technology is that columns and slabs were joined together by post-tensioning in two orthogonal horizontal directions at each floor level. Cast-in-situ RC shear walls were also provided; hence the lateral load-resisting system is a dual frame-wall system. Building height ranged from 6 to 20 storeys. Key features of the system were described by Dimitrijević (2002) and Dimitrijević and Gavrilović (2000), while a seismic design example was presented in UNIDO (1983). Examples of buildings in Belgrade constructed using the IMS construction technology in the 1970s were presented by Jovanović Popović and Ignjatović (2011), including a 17-storey residential building in Block 21, New Belgrade, and a few other examples (Fig. 15).

4.4 Evolution of rural and urban residential building typologies in Belgrade

The evolution of urban areas in Serbia can be followed from the second half of the nineteenth century. A discussion on the historical evolution of residential construction in Belgrade, the capital and the largest city of Serbia, is relevant for understanding the differences in building typologies and construction practices and will be discussed in this section.

Initially, dwellings in Belgrade were single-family houses similar to rural building typologies (type W). The prevalent construction was timber frame with infills, and some of these buildings are still present in the centre of Belgrade. Rural dwellings have been

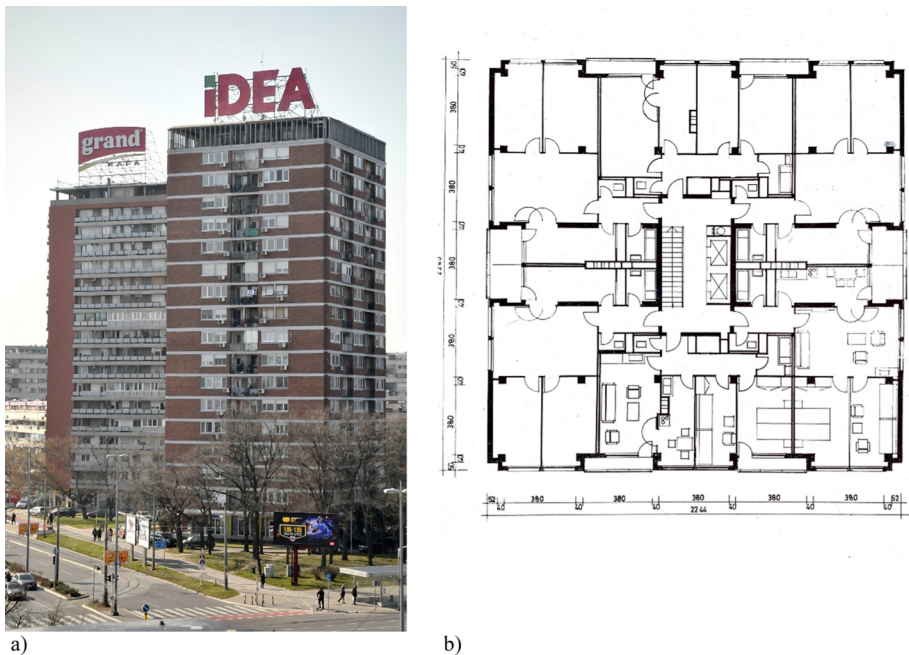


Fig. 15 Prefabricated RC building typologies—type RC3: **a** a 17-storey multi-family residential building in New Belgrade (Block 21), a part of the complex “The six corporals” constructed in the early 1960s using the IMS technology, and **b** a typical floor plan, showing column grid and RC structural walls (Zanko 1965)

traditionally constructed either by house owners or master builders, such as *Manakova kuća* (the Manak's House) at Savamala. The choice of construction technology was primarily governed by the availability of construction materials and artisan skills. The transition from rural to urban typologies was marked by timber frame buildings with brick infills (Đukanović 2021). A notable distinction in urban residential construction appeared in the second half of the nineteenth century, when the first multi-storey buildings, characterized by brick masonry walls and wooden floor structures (type M2), were built in the Knez Mihajlova Street in the centre of Belgrade (Jovanović Popović et al. 2013c).

Significant expansion and urbanisation of Belgrade and other cities in Serbia took place after WWI. The number of urban inhabitants in the Kingdom of Yugoslavia increased from 11,984,911 in 1921 to 15,919,000 in 1940 (Vuksanović-Macura 2014). Urban residential buildings increased in height (up to 5 storeys), and were usually built as housing in a row, thus creating new city blocks. Load-bearing walls were made from brick masonry, while the floor structures were mostly semi-prefabricated ribbed RC slabs, known as the Herbst system (type M3) (Jovanović Popović et al. 2013c). Great destruction in WWII, compounded by another increase in the number of inhabitants, prompted a need for fast reconstruction of the city and the construction of new residential blocks. At that time, unskilled workers were familiar with the traditional construction practices but were not familiar with the concrete construction technology (Jovanović 2017). Load-bearing structures were still constructed using brick masonry walls, and semi-prefabricated ribbed RC slabs, known as the Avramenko system (type M3). In the 1950s high-rise buildings (10-storeys or higher) were constructed in the city using concrete technology (type RC1 and type RC2). At the same time, government-owned construction companies started experimenting with new development and implementation of prefabricated construction technologies. At the initial stage, the IMS system (dual frame-wall system) was most widely used in Belgrade, along with Yugomont, a prefabricated large panel system (type RC3) (Jovanović 2017). Extensive use of these prefabricated systems started after the 1960s, with the development of building complexes (called “blocks”) in “new cities”, such as New Belgrade, which is located on the left coast of the Sava River in Belgrade (Mrduljaš 2012). These building blocks, constructed from the 1960s until the 1980s, represent a major fraction of the residential building stock of that period in Serbia. During the same period, reconstruction projects within the centre of the city were scarce, and the focus was on the development of new suburbs with multi-storey buildings (Ignjatović et al. 2013). Except for prefabricated building systems (type RC3), cast-in-situ RC technology was used for high-rise residential buildings (type RC2). The 1980s presented a return to housing in a row and traditional cast-in-place RC frames with masonry walls (type RC1), and confined masonry for smaller buildings (M4) (Jovanović Popović et al. 2013c). The migrations in the 1990s have produced an increase in the number of inhabitants in the city and its outskirts where the majority of the 1990s residential building stock was erected. This led to the construction of new city zones with informal construction, such as Kaluderica. Most buildings were built using modular clay blocks and semi-prefabricated concrete and clay floors (TM and LMT system). These buildings could be classified as type M3 or M4, depending on the presence of RC confining elements. Another challenge of urban construction in Serbia in the 1990s was due to vertical (rooftop) extensions of existing masonry buildings, which caused a significant increase in seismic risk associated with these buildings. More recent construction, after the 2000s, shows that masonry technology is still present in most building typologies. Single-family housing has been constructed using confined masonry (type M4) while multi-family residential buildings have been usually built as a combination of RC frames and masonry infills, with or without structural walls (type RC1 or RC2). Prefabricated systems are no

longer used for residential construction. Figure 16 shows a partial map of the centre of Belgrade and illustrates building typologies presented in Table 2. It can be seen from the map that the centre of Belgrade showcases a variety of residential building typologies which are located close to one another.

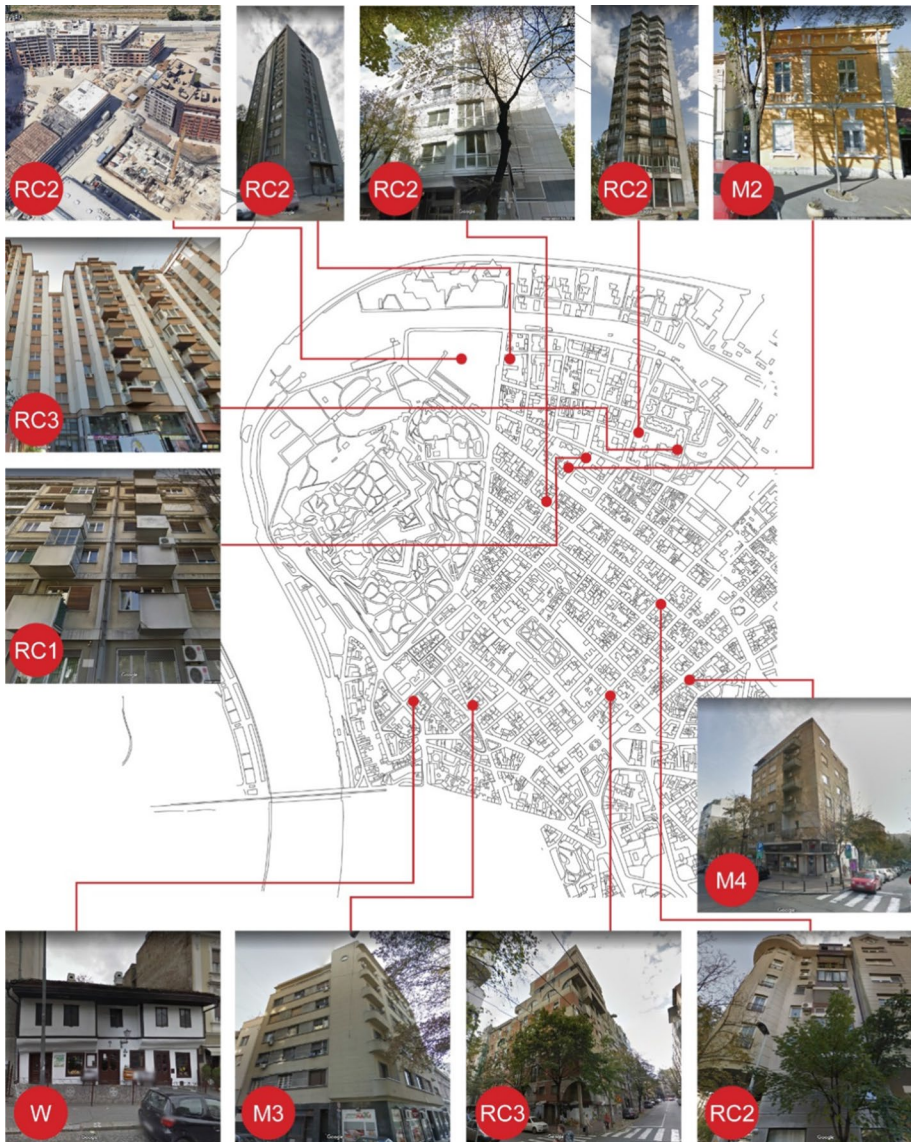


Fig. 16 Map of the centre of Belgrade showing examples of urban building typologies characteristic of major Serbian urban centres

5 Performance of residential buildings in past earthquakes in Serbia and neighbouring countries

5.1 Background

Consequences of past earthquakes in Serbia and the region are important for understanding the seismic vulnerability of buildings in Serbia. In the last 100 years, Serbia was affected by more than 10 earthquakes with a magnitude of 5.0 or higher. The most significant earthquake in the twentieth century occurred in 1922, with the epicentre near Lazarevac (approximately 60 km aerial distance from the capital Belgrade) and a magnitude of 6.0. Several other earthquakes affected rural areas, e.g., the 1927 Rudnik earthquake (M 5.9), the 1980 Kopaonik earthquake (M 5.8) and the 1998 Mionica earthquake (M_L 5.7). Since the beginning of the twenty-first century, the most damaging earthquake in Serbia occurred on November 3, 2010, with the epicentre close to the city of Kraljevo (M 5.5). Relevant past earthquakes in the region include the 1963 Skoplje earthquake (M 6.0), the 1969 Banja Luka earthquakes (M 5.6 and M 6.6), and the 1979 Montenegro earthquake (M_W 6.9). Two significant earthquakes which recently affected Croatia, namely the March 22, 2020 Zagreb earthquake (M_W 5.4) and the December 29, 2020 Petrinja earthquake (M_W 6.4), are relevant for Serbia due to similar construction practices and seismic design codes. Table 3 contains a summary of relevant earthquakes while the resulting building damage is discussed in the following text.

5.2 The July 26, 1963 Skopje earthquake

The July 26, 1963 Skopje earthquake (M 6.0) was the most catastrophic earthquake in the history of Yugoslavia. It caused at least 1500 deaths and more than 4000 injuries. At the

Table 3 A summary of the most important earthquakes in Serbia and the region (1963–2020)

Date	Location	Magnitude	Maximum intensity	Prevalent building typologies
July 26, 1963	Skopje, North Macedonia	6.0 M_W^a	9 ^a	W, M2, M3, RC1
October 27, 1969	Banja Luka, Republika Srpska, Bosnia and Herzegovina	6.2 M_W^a 6.4 M_L^a	8–9 ^a 9 ^b	M2, RC3
April 15, 1979	Montenegro	6.9 M_W^a 6.8 M_L^a	9–10 ^a	M1, M3, RC1, RC2
November 3, 2010	Kraljevo, Serbia	5.5 M_W^c	7 ^c	W, M2, M3, M4
March 22, 2020	Zagreb, Croatia	5.4 M_W^d	8 ^f	M2
December 29, 2020	Petrinja, Croatia	6.4 M_W^e	9 ^g	M2, M3, M4, RC1

^aGrünthal and Wahlström (2012), Grünthal et al. (2013)

^bTrkulja (2009)

^cSeismological Survey of Serbia (2010)

^dEMSC-CSEM (2022a)

^eEMSC-CSEM (2022b)

^fWikipedia (2020a)

^gWikipedia (2020b)

time of the earthquake Skopje was the capital of the Yugoslav Republic of Macedonia. The building stock in Skopje was severely affected—approximately 80% of the buildings were rendered unusable after the earthquake and had to be reconstructed (Sikošek 1986). Consequences of this earthquake were documented through reports (Arsovski et al. 1968; Poceski 1969; Paskalov et al. 1972) and videos (British Pathé 1963a). Unfortunately, acceleration records for the Skopje earthquake were not available, but a fault model was developed based on the aftershock distribution, the magnitude, the proposed source mechanism and the macroseismic intensity (Sudaholc et al. 2004) The recovery activities were also documented (British Pathé, 1963b; Milutinovic 2001).

The earthquake significantly affected URM buildings in the densely populated centre of Skopje, particularly low- to mid-rise multi-family residential buildings, which were prevalent form of housing in urban areas of Yugoslavia after WWII. These buildings were characterized by 38 cm thick clay brick masonry walls and ribbed RC floor slabs with RC ring beams (type M3-M according to the proposed classification).

Performance of type M3 buildings in the earthquake can be illustrated on the example of the Karpoš residential complex in the western part of Skopje, which was constructed in the 1950s (Berg 1964), Fig. 17a. The complex comprised of 40 buildings, with the height ranging from 3 to 5 floors. The buildings were designed according to standardized designs, with load-bearing walls provided only in one direction (either longitudinal or transverse). One of the densely populated 5-storey buildings (labelled No. 13) partially collapsed and caused 159 fatalities (Fig. 17b). Various damage patterns were observed in these buildings, ranging from in-plane shear cracks to horizontal offset at floor levels (Berg 1964). Detailed reports on post-earthquake surveys of these buildings are available (Milutinović 2022).

Three 14-storey RC apartment buildings in the Karpoš residential complex (called the Karpoš Towers) were also exposed to the 1963 Skopje earthquake (Berg 1964). The buildings had a cast-in-situ RC frame system with RC floors and can be classified as RC1-type buildings according to the proposed classification. The buildings had a rectangular plan, 43 m long and 15 m wide (Fig. 18). Lateral load-resisting system in the transverse direction consisted of parallel RC frames, at approximately 4.0 m spacing. The frames were discontinued at the stairwells. Plain concrete structural walls were provided in the longitudinal direction along two interior gridlines and around the stairwells. Rectangular RC columns had 70 cm by 35 cm cross-sectional dimensions, 6 longitudinal reinforcing bars

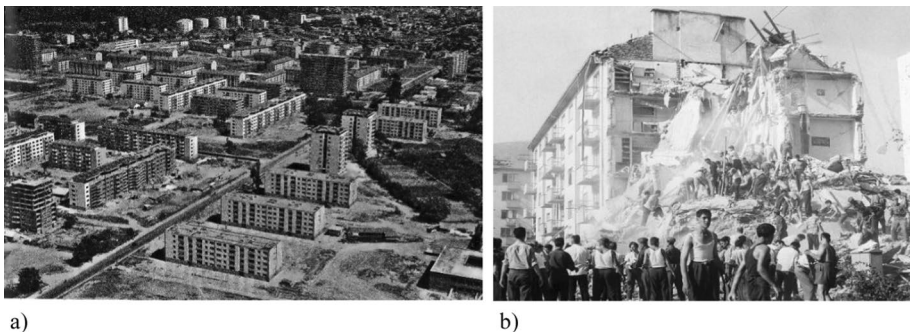


Fig. 17 Damage of masonry buildings (type M3) in the 1963 Skopje earthquake: **a** Karpoš building complex with 40 3–5 storey URM apartment buildings, and **b** a partially collapsed building No.13. (Source: Milutinovic 2022)

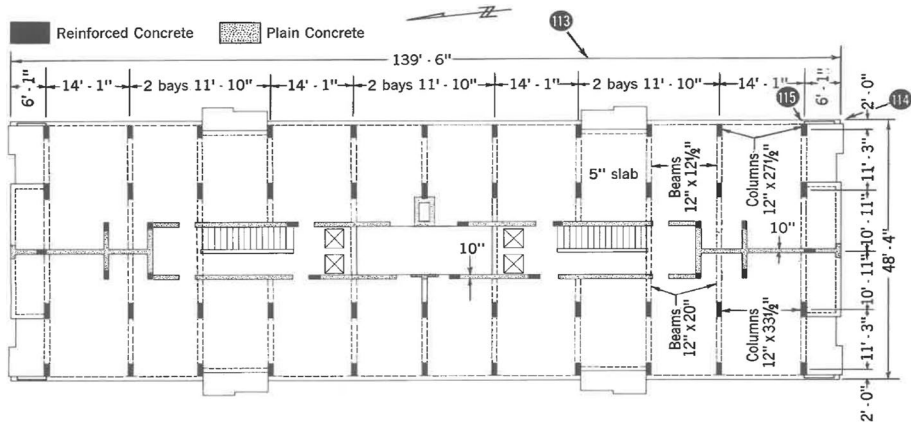


Fig. 18 Floor plan of Karpoš Tower, Skopje (Berg 1964)

(16–20 mm diameters) and 6 mm ties at 300 mm spacing. Concrete compressive strength of 20 MPa was specified by the original design. Two out of three towers experienced only minor damage, while the third tower experienced severe damage, including cracking in interior walls, horizontal cracking at the floor levels, and severe damage/failure of a corner RC column at the ground floor level (Fig. 19).

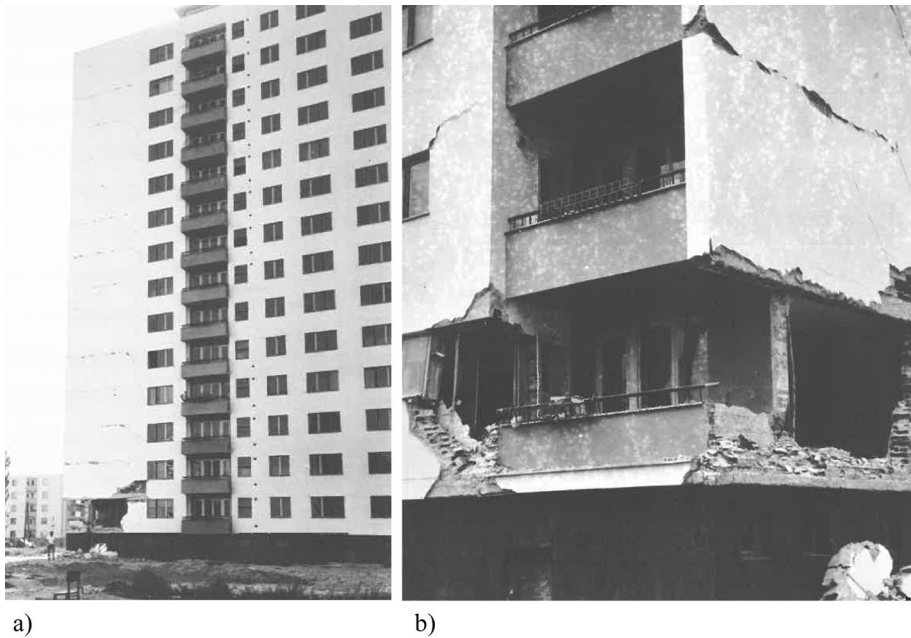


Fig. 19 Damage of RC buildings (type RC1) in Skopje due to the 1963 earthquake: **a** damaged Karpoš Tower (note the extensive damage at the ground floor level), and **b** a close-up of the damaged region (Berg 1964)

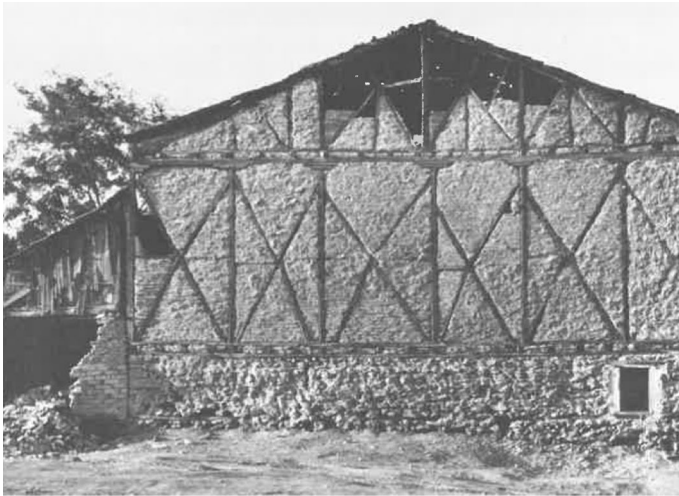


Fig. 20 Minor damage of a timber-framed house (type W) in the centre of Skopje due to the 1963 earthquake (Berg 1964)

At the time of the earthquake, several older timber-framed houses infilled with adobe bricks (*bondruk*) existed in Skopje (type W according to the proposed classification). A type W building shown in Fig. 20 was located close to the Karpoš residential complex and experienced only a minor damage, as opposed to severe damage and destruction of modern masonry buildings (Berg 1964).

5.3 The October 26 and 27, 1969 Banja Luka earthquakes

On October 26 and 27, 1969, the city of Banja Luka was hit by two damaging earthquakes. The first earthquake (M 5.6) served as a warning for the next event, which occurred 16 h later and was significantly stronger (M 6.6) (Trkulja 2009). These earthquakes caused 15 deaths, while 1,117 people were injured. More than 86,000 dwellings were affected and many experienced either damage or collapse. A total of 266 schools were either damaged or collapsed. The earthquakes also affected 146 cultural monuments, 133 health facilities and 152 public buildings (Davidović 2009). The URM buildings, many of which experienced either severe damage or collapse, were affected the most. The partial or total collapse of URM buildings with wooden floors and roofs, classified as type M2 in the proposed classification, was reported (Fig. 21). In many cases, the gable walls in these buildings experienced partial or total collapse. Video recordings offer an excellent illustration of the effects of these earthquakes (British Pathé 1969) and the recovery (Pejčinović-Bailey 2020).

The 1969 Banja Luka earthquakes exposed a number of prefabricated RC buildings to severe ground shaking. At the time, prefabricated RC technology was fairly new and there were no prior studies in Yugoslavia related to the seismic response of these buildings. It was reported that 17 prefabricated residential RC frame-wall buildings, ranging from 5 to 14 storeys in height, were constructed in the centre of Banja Luka, near the Crkvena River, using the IMS technology (described earlier in Section 4.3.8). According to the proposed classification, these buildings are representative of the RC3 type. The buildings were designed in the 1960s, likely without any seismic design considerations since Banja Luka

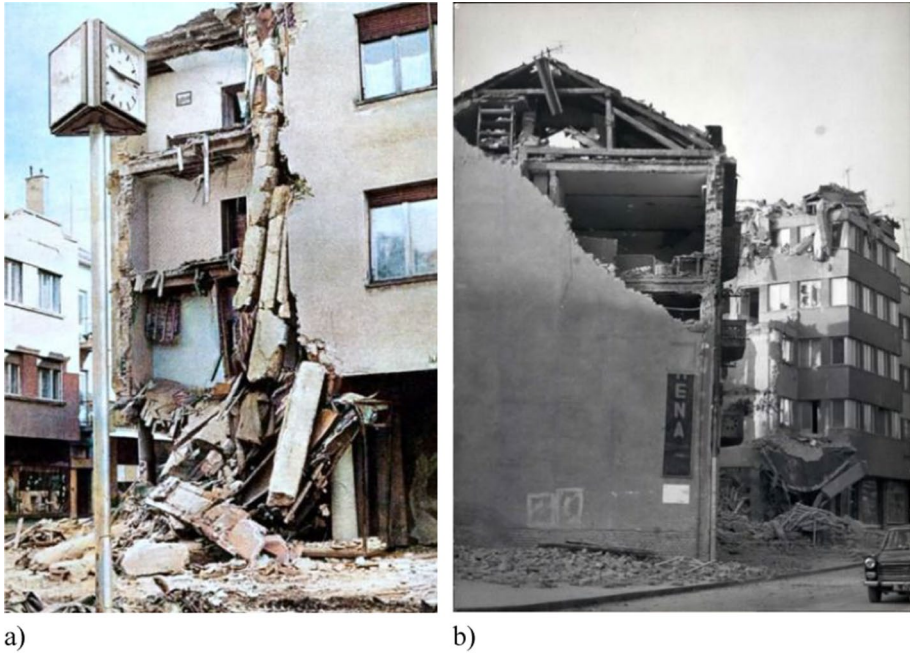


Fig. 21 Examples of type M2 residential URM buildings in Banja Luka affected by the 1969 earthquakes: **a** a partial collapse of the building with wooden floors (Banja Luka 2009) and **b** collapse of a gable wall (Blic 2019)

was not located in an earthquake-prone area according to the official seismic hazard map (UNIDO 1983). Buildings with RC structural walls, including two 14-storey towers which were the tallest buildings in Banja Luka at the time of these earthquakes, experienced either insignificant damage or remained undamaged (Fig. 22). However, a few of the IMS prefabricated RC buildings without structural walls experienced significant non-structural damage of the partition and façade walls and had to be repaired. Some of these buildings

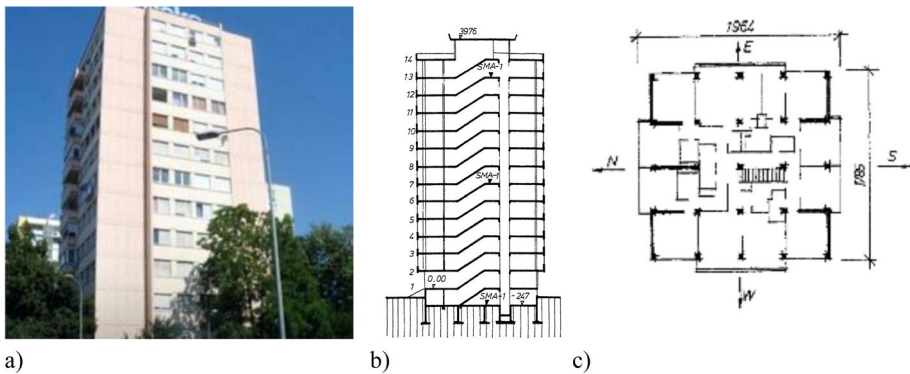


Fig. 22 An example of type RC3 prefabricated RC building in Banja Luka: **a** exterior view of a 14-storey residential building; **b** elevation, and **c** typical floor plan (Jurukovski et al. 1988)

were instrumented after the 1969 earthquakes, and their seismic response was analysed in detail after the 1981 Banja Luka earthquake (M 5.4) (Jurukovski et al. 1988).

5.4 The April 15, 1979 Montenegro earthquake

The April 15, 1979 Montenegro earthquake (M_w 6.9) is the strongest recorded earthquake in former Yugoslavia. The earthquake caused 101 deaths in Montenegro and 35 deaths in Albania. More than 1000 individuals were injured, and more than 80,000 people lost their homes (ZHMS 2014). The epicentre was located offshore in the Adriatic Sea, between Ulcinj (10 km epicentral distance) and Bar (25 km epicentral distance). The earthquake devastated many coastal settlements, which were among the most popular tourist centres in Yugoslavia, including the historic centres of Budva (53 km epicentral distance), Kotor (70 km epicentral distance), Risan, Petrovac, Herceg Novi and Dubrovnik. An intensity map for the 1979 Montenegro earthquake (ZHMS 2013) shows different intensities according to the Mercalli-Cancani-Sieberg (MCS) scale (Fig. 23). The map shows that the highest intensity (IX according to the MCS scale) was reported in the epicentral region, which was spanning over the 90 km distance. The earthquake was felt as far as 900 km away from the epicentre, but the damaging effects were limited to a 100 km long coastal region and a 25 km wide stretch from the coast toward the mountains (ZHMS 2014).



Fig. 23 Intensity map for the 1979 Montenegro earthquake (ZHMS 2013)

Out of 57,640 buildings surveyed after the earthquake, 92% were constructed using stone masonry. It was estimated that, out of all surveyed buildings, approximately 22% were classified as severely damaged or collapsed and had to be reconstructed. Besides the residential buildings, the earthquake severely affected majority of hotels in the region, 240 schools, 53 health facilities, and other public buildings. The earthquake also affected 1487 cultural heritage structures, including churches, monasteries, and museums (UNESCO 1984). The consequences of this major earthquake were documented through videos (TV IN 2011; RTCG 2016). A detailed overview of building performance in the earthquake was presented by Aničić (1980) and Fajfar et al. (1981) and served as the main resource for this section.

Older stone masonry buildings with wooden floors and roofs (type M1) were mostly 2- to 4-storey high and were severely affected by the earthquake. Three-wythe stone masonry walls in these buildings had exterior wythes constructed using semi-shaped stone in lime mortar, while interior wythes were filled with rubble. In most cases, these walls were heavily damaged or collapsed due to the lack of connections between the exterior wall wythes, inadequate building integrity, e.g., lack of connections between intersecting walls, and due to inadequate wall-floor connections. Historic centres of Budva (Fig. 24a) and Kotor (Fig. 24b) had the largest stocks of stone masonry buildings, which experienced severe damage or collapse, despite being located at 50–70 km distance from the epicentre. It was observed that some of the well-constructed stone masonry buildings remained undamaged in the earthquake, e.g., buildings in the centre of Kotor, Fig. 24c (Aničić, 1990).

Brick masonry buildings with rigid RC floors (type M3) were not common in the area, mostly due to the prevalence of stone masonry construction. However, the Budva Town Hall was a relatively large building with 3 floor levels, constructed with brick masonry walls and semi-prefabricated ribbed RC floor slabs (Avramenko), Fig. 25. Although the building did not have RC ring beams, it demonstrated the seismic behaviour typical of buildings with rigid diaphragms. The damage was in the form of X-shaped shear cracks, mostly located in the wall piers at the ground floor level.

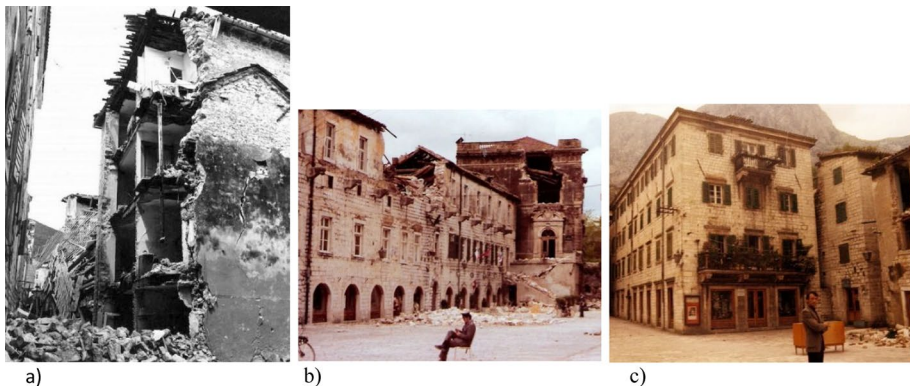


Fig. 24 Examples of type M1 stone masonry buildings in Montenegro affected by the 1979 earthquake: **a** a street in the historic centre of Budva, showing collapse of stone masonry buildings with wooden floors (RTV Budva 2015); **b** damaged buildings in the historic centre of Kotor (Cafe del Montenegro 2016), and **c** undamaged stone masonry buildings in the centre of Kotor (Petrović 1979)



Fig. 25 Budva Town Hall—an example of a type M3-M building damaged in the 1979 Montenegro earthquake (M. Fischinger)

Hotel “Slavija” in Budva was constructed after WWII (Fig. 26a). It comprised of three near-identical, rectangular-shaped 4-storey building blocks (type RC1). The hotel had an open-space restaurant at the ground floor level, while at the upper floors brick masonry infills were constructed between the rooms. The lateral load-resisting system consisted of RC frames in the transverse direction, but there were neither frames nor structural walls in the longitudinal direction. The floor structure consisted of ribbed RC slabs, which formed a column-slab system in the longitudinal direction. One of the hotel blocks collapsed in the earthquake (Fig. 26b), while the other two blocks experienced severe damage, particularly at the ground floor level, showing signs of instability and the *soft storey* failure mechanism (Fig. 26c). Several RC columns at the ground floor level experienced damage, extending to the slab at the top, due to high seismic drift demand.

Hotel “Oliva” in Petrovac, a small coastal town located 18 km south of Budva, was a 4-storey RC frame structure constructed after WWII (Fig. 27a). RC structural walls (type RC2) were constructed as a part of the retrofit project after the earthquake which hit the region in 1966. The columns were provided at approximately 4 m spacing in the longitudinal direction, and 5 m spacing in the transverse direction. Circular RC columns at the ground floor level were severely damaged, and plastic hinges formed at the base (Fig. 27b). RC structural walls at the second-floor level experienced severe damage in the form of shear cracks, which indicated inadequate horizontal reinforcement (Fig. 27c). Lateral drift demand in the (more flexible) longitudinal direction caused significant damage in partitions located at the second-floor level.

5.5 The November 3, 2010 Kraljevo earthquake

The most damaging earthquake in Serbia in the twenty-first century occurred on November 3, 2010, with the epicentre close to the Sirča village located 4 km from Kraljevo, a mid-size Serbian city (population 68,000). The earthquake had a magnitude (M_w) of 5.5, causing 2 fatalities and financial losses estimated at more than \$US 100 million (World Bank 2017). It was reported that approximately 16,000 single-family dwellings (houses) in Kraljevo and the neighbouring villages experienced damage or collapse due to the earthquake; out of those, approximately 500 houses were replaced and 2000 houses required structural repairs (MUP 2010). The earthquake caused the collapse of a significant number



a)



b)



c)

Fig. 26 Damage of the Hotel “Slavija” buildings (type RC1) in Budva due to the 1979 Montenegro earthquake: **a** an exterior view of the hotel before the earthquake (FOS Media 2020); **b** the collapsed block, and **c** a column damage detail (Petrović 1979)

of single-family houses and damaged many other structures, including multi-family apartment buildings, educational and health facilities, heritage structures, etc. A detailed overview of the performance of masonry buildings in the Kraljevo earthquake was presented elsewhere (Manić and Bulajić 2013, 2014).



a)



b)



c)

Fig. 27 Damage of the Hotel “Oliva” building in Petrovac (type RC2) due to the 1979 earthquake: **a** an exterior view of the building showing the damaged RC structural walls at the second floor level; **b** damaged base of a circular RC column at the ground floor level, and **c** extensive damage of an RC structural wall (Petrović, 1979)

Masonry buildings accounted for more than 90% of the building stock in the 2010 Kraljevo earthquake-affected area. A survey of the damaged buildings showed that severe damage and/or collapse of single-family URM dwellings, classified as type M2 according to the proposed classification, was due to the poor quality of building materials and construction, flexible floor/roof diaphragms, and/or poorly planned and executed renovations and extensions, Fig. 28a (Manić and Bulajić 2013, 2014). In some cases, older timber-frame (*bondruk*) houses remained undamaged, while adjacent new masonry buildings experienced damage (Fig. 28b). Modern confined masonry buildings (type M4), with properly constructed RC confining elements, performed well in the earthquake (Fig. 29c); however, buildings with inadequately reinforced confining elements and walls with



Fig. 28 Rural single-family masonry buildings affected by the 2010 Kraljevo, Serbia earthquake: **a** a severely damaged type M2 building; **b** a damaged inadequately confined M4 type building (left) adjacent to an undamaged old timber-frame (bondruk) building; **c** and **d** damage at the corners of the building shown in figure **b** due to construction flaws (Manić and Bulajić 2014)

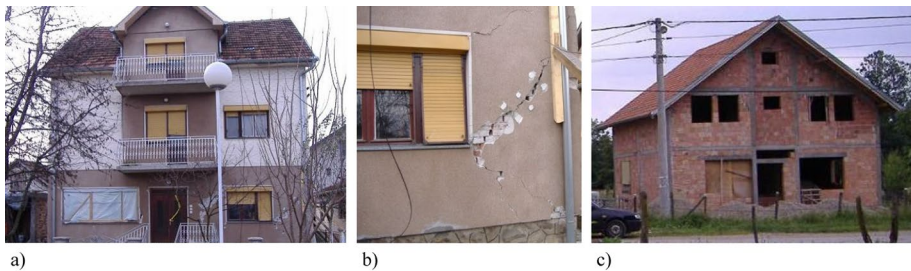


Fig. 29 Performance of type M4 single-family buildings in the 2010 Kraljevo, Serbia earthquake: **a** a partially confined building (ground floor unconfined and upper floors confined); **b** damage of the same building at the ground floor level, and **c** a fully confined M4 type building under construction remained undamaged (Manić and Bulajić 2014)

horizontally aligned perforations in modular clay blocks experienced damage (Fig. 28c and d and Fig. 29a and b).

Several multi-family apartment buildings (3- to 5-storey high) were damaged in the 2010 Kraljevo earthquake and required repair and/or retrofit (Ostojić et al. 2011, 2012). These were URM buildings with ribbed RC floor slabs and RC ring beams that can be

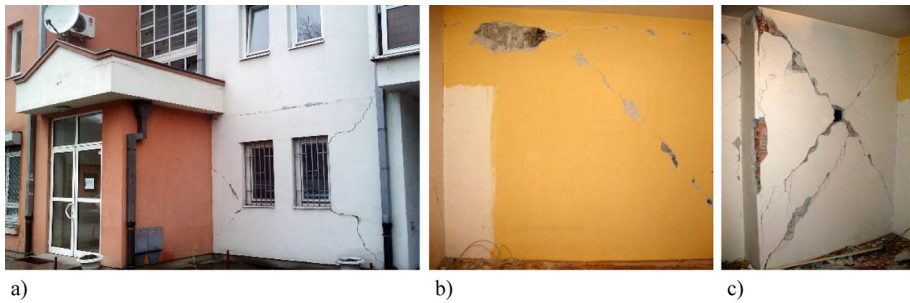


Fig. 30 Performance of type M3-M multi-family residential buildings in the 2010 Kraljevo, Serbia earthquake: **a** diagonal and horizontal cracks in an exterior wall; **b** in-plane damage of a load-bearing interior wall (solid clay bricks), and **c** extensive cracking in a partition wall (multi-perforated clay blocks) (Blagojević 2022)

treated as rigid diaphragms and are classified as M3-M type according to the proposed classification. Exterior structural damage was limited to the walls located at the bottom floors (usually the ground floor), in the form of inclined cracks typical for diagonal tension shear failure (Fig. 30a). Horizontal cracks were observed in the exterior walls at each floor level, due to high seismic demand which caused debonding at the masonry-concrete interface (Fig. 30b). Non-structural damage was observed in partition walls at the upper floors, particularly in the extended portion of the building (top floor), Fig. 30c. Non-structural damage in partition walls was usually caused by combined in-plane and out-of-plane seismic actions.

5.6 The 2020 Croatia earthquakes

Recently, two damaging earthquakes occurred in Croatia, namely the March 22, 2020 Zagreb earthquake (M_w 5.5), and the December 29, 2020 Petrinja earthquake (M_w 6.4). These earthquakes mostly affected older URM buildings in historic urban centres (Stepinac et al. 2021; Miranda et al. 2021; Markušić et al. 2020, 2021). The epicentre of the 2020 Zagreb earthquake was located approximately 7 km northeast of Zagreb's centre. The earthquake caused one fatality, 26 people were injured, and thousands of inhabitants were temporarily displaced from their homes. In spite of a moderate magnitude, the earthquake caused a significant damage. Out of more than 26,000 building assessments, 1900 buildings were classified as uninhabitable and had to be reconstructed (Šavor Novak et al. 2020; Atalić et al. 2021). A total of 6651 buildings located in the historic centre of Zagreb were damaged (Stepinac et al. 2021). Majority of the damaged buildings can be classified as type M2, and one of the most common failure patterns was the collapse of gable walls (Fig. 31a). Notably, most of the buildings built after 1990 suffered little or no damage.

The Petrinja earthquake of December 29, 2020 (M_w 6.4) caused 7 deaths, 26 people were injured, while several hundred people were displaced (Miranda et al. 2021). More than 50,000 buildings were surveyed, out of which more than 40% were classified as damaged (HCPI 2021). Severe damage was observed in older URM buildings with flexible wooden floors (type M2), Fig. 31b), while only a few URM buildings with rigid floors (type M3) experienced damage (Fig. 32a). Majority of properly constructed confined

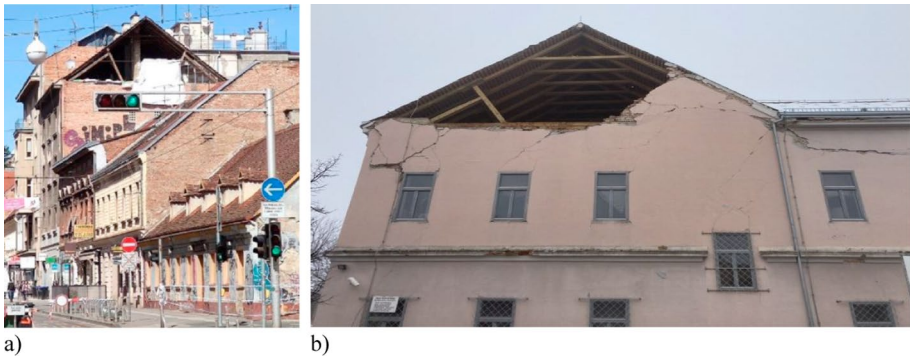


Fig. 31 Damage of URM buildings (type M2) due to the 2020 Croatia earthquake: **a** typical damage due to the March 2020 Zagreb earthquake (Stepinac et al. 2021) and **b** typical damage due to the December 2020 Petrinja earthquake (SUZI-SAE 2021)

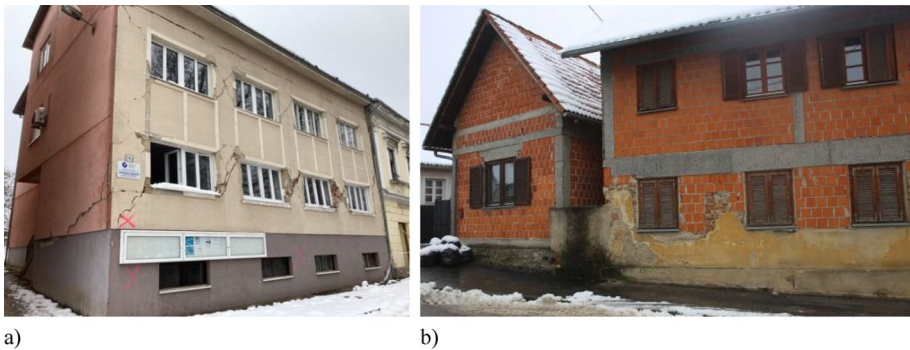


Fig. 32 Damage of masonry buildings due to the December 2020 Petrinja, Croatia earthquake: **a** significant in-plane shear cracking in an M3 building in Petrinja and **b** undamaged type M4 buildings in Petrinja (SUZI-SAE 2021)

masonry buildings (type M4) did not suffer significant damage (Fig. 32b). Several school buildings with masonry-infilled RC frames (type RC1) experienced damage, mostly in the form of cracking and failure of infill walls. A five-storey residential RC building in Petrinja experienced damage in RC columns at the open ground floor due to a soft storey mechanism (Fig. 33).

6 Seismic vulnerability of residential buildings in Serbia

6.1 Damage classification

Damage state (DS) is an important indicator of either expected or reported earthquake damage for a specific building or a building typology. DS is, also, an important indicator for estimating potential earthquake losses after an event, but can be also used for pre-event seismic risk and resilience studies. Damage classification scales usually identify



Fig. 33 Damage of type RC1 residential building in Petrinja, Croatia due to the December 2020 earthquake: **a** exterior view showing open ground floor space which used as a store before the earthquake, and **b** a detail of the damaged RC column (SUZI-SAAE 2021)

3 to 5 DSs, ranging from minor damage to collapse/destruction (Anagnostopoulos et al. 2004; Baggio et al. 2007; FEMA 1999).

Damage state classification scales apply to various lateral load-resisting systems, e.g., load-bearing masonry walls or RC frames with masonry infills. DSs for masonry buildings are associated with an increasing extent of cracking in load-bearing masonry walls and partitions, while DSs for RC buildings with masonry infills characterize the extent of damage both in RC components and masonry infill walls and partitions.

The European Macroseismic Scale 1998 (EMS-98) has been used in this study because it has been widely accepted in Europe and is relatively easy to use (Grünthal 1998). This section presents the EMS-98 damage classification for RC and masonry buildings, with a focus on two common building typologies in Serbia: cast-in-situ RC frames with masonry infills (RC1) and URM buildings with rigid floors (M3). Examples of various DSs for RC1 and M3 building typologies, as reported in past earthquakes in Serbia and neighbouring countries, are presented in Tables 4 and 5.

6.2 Expert-based seismic fragility functions for the Serbian building stock

Seismic fragility functions provide a probabilistic relation between the seismic hazard intensity measures and the expected building DSs and are a core tool for quantitative seismic risk assessment of buildings (Pitilakis et al. 2014; FEMA 2020). When combined with seismic hazard models, exposure data, and consequence models, seismic fragility functions are used to obtain risk-based estimates of potential seismic losses for a region in terms of casualties, repair costs, and building downtime.

Fragility functions can be generated using empirical, analytical, expert-based, or hybrid methods (Porter 2015). Empirical methods apply statistical analysis to post-earthquake building damage data to derive fragility functions (Rosti et al. 2021; Formisano and Chieffo 2023); however, their accuracy and availability are conditioned on the available data, which can be scarce, especially in regions with low to moderate

Table 4 EMS-98 damage classification for buildings with cast-in-situ RC frames and masonry infills (type RC1)


Damage state	Description (Grünthal 1998)	Example from a past earthquake
<p><i>Damage State 1 (DS1): Negligible to slight damage</i></p> <p>No structural damage, slight non-structural damage</p>	<p><i>RC frame:</i> Fine cracks in plaster over frame members at the base; <i>Masonry infills and partitions:</i> Fine cracks in partitions and infills</p>	
Example	Light cracks in plaster in the infill masonry walls	<p>Gymnasium in Primary School “Dragutin Tadijanović”, Petrinja (SUZI-SAAE) December 29, 2020 Petrinja, Croatia earthquake $M_w = 6.4$, $I (^{\circ}MCS) = 9$</p>

Table 4 (continued)


Damage state	Description (Grünthal 1998)	Example from a past earthquake
<p><i>Damage State 2 (DS2): Moderate damage</i> Slight structural damage, moderate non-structural damage</p>	<p><i>RC frame:</i> Cracks in columns and beams; <i>Masonry infills and partitions:</i> Cracks in partitions and infill walls; fall of brittle cladding and plaster; falling mortar from the joints of wall panels</p>	
<p>Example</p>	<p>Cracking of interior infill walls; spalling of plaster; damage at the infill-frame interface; cracking of RC columns</p>	<p>Retirement home, Petrinja (SUZI-SAPEE) December 29, 2020 Petrinja, Croatia earthquake $M_W = 6.4, I (\text{°MCS}) = 9$</p>

Table 4 (continued)


Damage state	Description (Grünthal 1998)	Example from a past earthquake
<p><i>Damage State 3 (DS3): Substantial to heavy damage</i></p> <p>Moderate structural damage, heavy non-structural damage</p>	<p><i>RC frame:</i> Cracks in columns and beam-column joints of frames at the base; spalling of concrete cover, buckling of reinforcement rods;</p> <p><i>Masonry infills and partitions:</i> Large cracks in partitions and infill walls; failure of individual infill panels</p>	
<p>Example</p>	<p>Cracking in interior infills; failure of exterior walls and RC columns with inadequate confinement (amount of horizontal reinforcement) at the first-floor level</p>	<p>Karpoš Tower, Skopje (Berg 1964) 1963 Skopje earthquake $M_W = 6.0$, $I (°MCS) = 9$</p>

Table 4 (continued)


Damage state	Description (Grünthal 1998)	Example from a past earthquake
<p><i>Damage State 4 (DS4): Very heavy damage</i> Heavy structural damage, very heavy non-structural damage</p>	<p><i>RC frame:</i> Large cracks in structural elements with compression failure of concrete and fracture of rebars; bond failure of beam reinforcement; tilting of columns; collapse of a few columns or a single upper floor <i>Masonry infills and partitions:</i> Information not available</p>	
<p>Example</p>	<p>Hotel “Slavija”, Budva (Petrović, 1979) 1979 Montenegro earthquake $M_w = 6.9, I (^{\circ}MCS) = 9$</p> <p>Significant damage of RC structure at the ground floor level—instability and onset of the “Soft-storey” failure mechanism; buckling of reinforcement at the top of RC columns at ground floor level</p>	

Table 4 (continued)

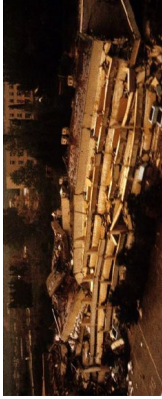
Damage state	Description (Grünthal 1998)	Example from a past earthquake
<i>Damage State 5 (DSS): Destruction</i> Very heavy structural damage	Collapse of ground floor or parts (e.g. wings) of buildings	
Example	Complete collapse of a RC frame structure with brick masonry infills which was designed without seismic considerations (Fajfar et al. 1981)	Hotel complex “Slovenska Plaža”, Budva (Petrović, 1979) 1979 Montenegro earthquake $M_w = 6.9$, $I (^{\circ}\text{MCS}) = 9$

Table 5 EMS-98 damage classification for URM buildings with rigid floors (type M3)



Damage state	Description (Grünthal 1998)	Example from a past earthquake
<p><i>Damage State 1 (DS1): Negligible to slight damage</i> No structural damage, slight non-structural damage</p>	<p>Hairline cracks in very few walls Fall of small pieces of plaster only Fall of loose stones from upper parts of buildings in very few cases</p>	 <p>Residential building in Petrinja (SUZI-SAEI) December 29, 2020 Petrinja, Croatia earthquake $M_w = 6.4, I (^{\circ}MCS) = 9$</p>
<p><i>Damage State 2 (DS2): Moderate damage</i> Slight structural damage, moderate non-structural damage</p>	<p>Hairline cracks in some exterior walls (mostly in the window corners); most of the walls are undamaged Cracks in many walls Fall of large pieces of plaster Partial collapse of chimneys</p>	 <p>A residential building in Kraljevo (Blagojević, 2022) 2010 Kraljevo, Serbia earthquake $M_w = 5.5, I (^{\circ}MCS) = 7$</p>

Table 5 (continued)

Damage state	Description (Grünthal 1998)	Example from a past earthquake
<p><i>Damage State 3 (DS3): Substantial to heavy damage</i></p> <p>Moderate structural damage, heavy non-structural damage</p>	<p>Large and extensive cracks in most walls</p> <p>Roof tiles detach</p> <p>Chimneys fracture at the roof line</p> <p>Failure of individual non-structural elements (partitions, gable walls)</p>	 
<p>Example</p>	<p>In-plane shear cracks in load-bearing walls; most of the walls were damaged; failure of partition walls</p>	<p>Residential building in Petrinja (SUZI-SAEI)</p> <p>December 29, 2020 Petrinja, Croatia earthquake</p> <p>$M_W = 6.4$, $I (^{\circ}\text{MCS}) = 9$</p>

Table 5 (continued)



Damage state	Description (Grünthal 1998)	Example from a past earthquake
<p><i>Damage State 4 (DS4): Very heavy damage</i> Heavy structural damage, very heavy non-structural damage</p>	<p>Significant damage and failure of walls Partial structural failure of roofs and floors</p>	
<p>Example</p>	<p>Severe damage of masonry walls in the form of shear cracks. Partial failure at the corner</p>	<p>Chamber of Crafts in Petrinja (SUZI-SAEI) December 29, 2020 Petrinja, Croatia earthquake $M_w = 6.4$, $I(\text{MCS}) = 9$</p>

Table 5 (continued)

Damage state	Description (Grünthal 1998)	Example from a past earthquake
<i>Damage State 5 (DSS): Destruction</i> Very heavy structural damage	Total or near total collapse	
Example	Partial collapse of building No. 13, which had load-bearing masonry walls only in one direction (Berg 1964)	Karpoš residential complex, Skopje (Militinović, 2022) 1963 Skopje earthquake $M_w = 6.0$, $I (^{\circ}\text{MCS}) = 9$

seismicity. Analytical methods are based on simulating the seismic response of buildings, thus providing building damage data that can be used to calibrate fragility functions, e.g., Martins and Silva (2020) and Abbiati et al. (2021). Risk modellers are often required to make numerous non-standardized modelling choices, ranging from ground motion record selection to the complexity level of the structural model, which affect the derived fragility functions (Silva et al. 2019). Expert-based methods rely on experts' experience to estimate potential building damage, which is then statistically analysed to calibrate the fragility functions (ATC-138 2022; Jaiswal et al. 2014; Porter et al. 2007). The drawbacks of expert-based methods are the often-limited experts' experience, as well as their subjectivity.

Analytical fragility functions developed specifically for the Serbian building stock are not yet available (Martins and Silva 2020), however, a few recent studies have contributed to an improved understanding of the vulnerability of masonry buildings in Serbia. A study on 1193 residential masonry buildings damaged in the 2010 Kraljevo earthquake was performed using the information from the post-earthquake survey forms collected by the City of Kraljevo (Stojadinović et al. 2017; Marinković et al. 2018). Empirical fragility functions were derived based on the collected data.

This section presents expert-based fragility functions derived for common building typologies in Serbia and neighbouring countries which were a part of former Yugoslavia. A few moderate-intensity earthquakes which occurred in the region in the last 12 years, e.g., the 2010 Kraljevo, Serbia earthquake and the 2020 Croatia earthquakes, exposed the local structural engineers to post-earthquake damage assessment and reconstruction activities. The goal of our study was to harness the experience gained in the recent earthquakes by seeking expert estimates, and formalizing them into fragility functions for common building typologies in the region. The limitations of experts' experience also have to be acknowledged: majority of the damaged buildings in recent earthquakes were URM structures, thus, the experts were most familiar with seismic performance of URM building typologies. The fact is that a relatively small number of confined masonry and RC structures were affected by these earthquakes. Therefore, the presented results are most reliable in the context of URM structures. Experts' opinions were collected using an online questionnaire that consisted of two sections. In the first section, the experts (structural engineers) were requested to declare professional experience related to post-earthquake damage assessment and/or retrofit, and number of years of engineering experience. The second section of the questionnaire consisted of two questions which were posed for each of the 10 different buildings (Fig. 34). Each building was illustrated by a photo showing an exterior view of the building (Fig. 34). These buildings were chosen to represent the most common building types in Serbia, including RC structures (types RC1, RC2, and RC3), URM structures with flexible diaphragms (type M2) and rigid diaphragms (type M3-S and M3-M), as well as confined masonry structures (type M4).

Initially, the experts were asked to infer the building typology (structural type) based on the provided building photo. Lack of exposure data related to a building's structural type is a common issue in seismic risk assessment: hence, a way to collect such data is by visually inferring the building's structural type. The authors used this questionnaire to examine the consistency in attributing structural types to buildings based on their exterior appearance.

Subsequently, the experts were asked to estimate the expected DSs which a building would experience due to an earthquake of a certain intensity, ranging from 5 to 9 according to the MCS scale. The descriptions for DSs were based on the EMS-98 (Grünthal 1998). The authors believe this is an appropriate method for collecting expert judgement, considering that most experts are familiar with the EMS-98 damage scale and the MCS

Building 1/10



1. Which structural type best describes the structural type of the building shown in the figure above?

- Reinforced-concrete structure
- Masonry structure with vertical and horizontal confinement
- Masonry structure without vertical confinement and rigid diaphragms
- Masonry structure without vertical confinement and flexible diaphragms

Table with descriptions of MCS earthquake intensity scale

Table with descriptions of EMS-98 damage scale for masonry structures

Table with descriptions of EMS-98 damage scale for reinforced-concrete structures

2. Estimate the expected damage state of the building shown in the figure above for different earthquake intensities defined according to MCS scale:

	Earthquake Intensity: MCS V	Earthquake Intensity: MCS VI	Earthquake Intensity: MCS VII	Earthquake Intensity: MCS VIII	Earthquake Intensity: MCS IX
No damage					
DS 1					
DS 2					
DS 3					
DS 4					
DS 5					
Don't know					

3. Optional Comment

Fig. 34 Example of a questionnaire page for a single building (translated to English)

earthquake intensity scale. The proposed method resembles the post-earthquake damage assessment, except that in this study the experts were asked to estimate the damage that a building may experience in an earthquake, as opposed to identifying the DS for a damaged building. Alternative approaches for deriving expert-based fragility functions are also available (Porter et al. 2007).

The questionnaire was filled out anonymously by 40 experts from Serbia, Croatia, North Macedonia, Bosnia and Herzegovina, and Montenegro. Out of 40 experts in total, 27 (i.e., 67%) had previous experience in post-earthquake damage assessment and/or retrofit. On average, the experts had 15 years of structural engineering experience.

Table 6 summarises the results of building typology inference based on the photo of the building's exterior. Detailed descriptions of building typologies are presented in Sect. 4. The experts generally provided consistent opinions on building typology that agreed with the opinion of the authors. This finding increases the confidence in using a visual inspection of a building exterior to collect the building typology exposure data. Unfortunately, the actual structural types of buildings are not known.

To obtain the DS fragility functions, the MCS earthquake intensities were transformed into peak ground acceleration (PGA) values using the median values from the Eq. 1, presented in Sect. 2, as proposed by Trifunac et al. (1991). Experts' judgement was statistically analysed for each PGA value to obtain the probabilities of attaining or exceeding each DS. For each DS, a count of how many experts estimated that the structure will be in or exceed the DS at each PGA value was performed. The count was normalized by the total number of experts that provided an estimate to get the probability of exceedance for each DS at each PGA value. Such probability was assumed to be an outcome of a binomial distribution. Then, using the maximum likelihood method and the statistical analysis of experts' judgement, the parameters of lognormal DS fragility functions (i.e., the median μ and the standard deviation of logged values β) for each building were derived. The likelihood function was obtained as a product of binomially distributed variables at each PGA value. The method is analogous to the fragility function fitting (Baker 2015). However,

Table 6 Results of inferring the building's structural type based on the photo of the building's exterior for each considered building (highlighted fields represent the authors' judgement)

Structural type Building ID	M2	M3	M4	RC1, RC2, RC3
1	0	4	35	1
2	29	8	3	0
3	0	0	3	37
4	0	0	1	39
5	0	0	2	38
6	2	29	8	1
7	0	0	5	35
8	29	9	2	0
9	0	0	2	38
10	1	10	28	1

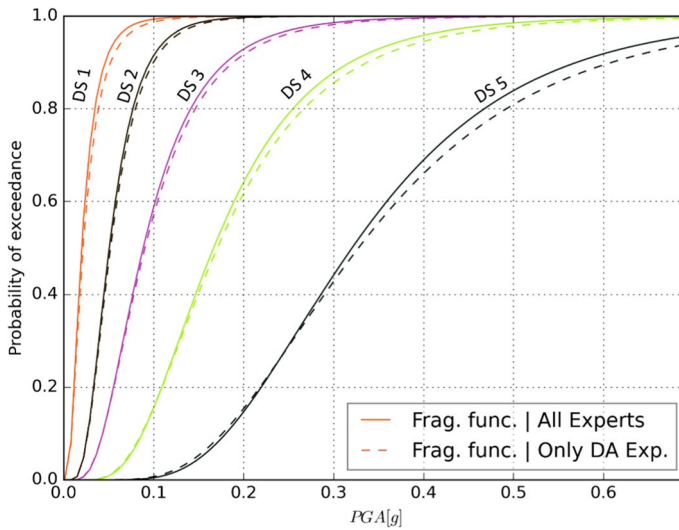


Fig. 35 Fragility functions for the URM building with rigid floors (type M3-M) derived from expert judgement for different DSs. Solid lines are the DS fragility functions derived based on the opinion of all 40 experts that filled the questionnaire (“All Experts”), while dashed lines are the DS fragility functions derived based only on the opinion of experts with post-earthquake damage assessment experience (“Only DA Exp.”)

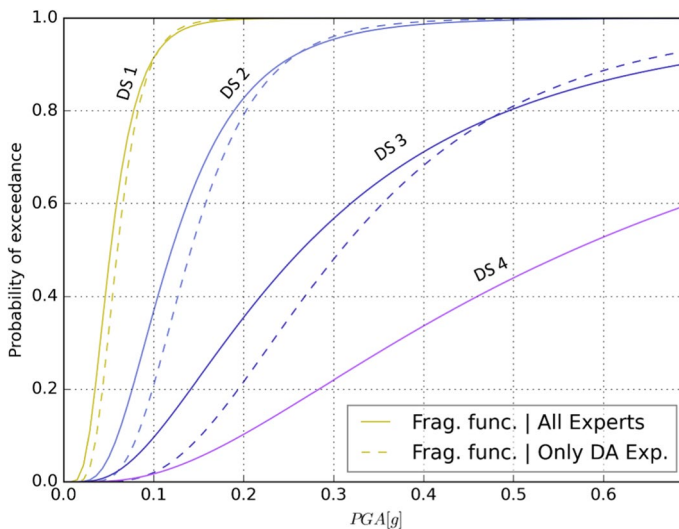


Fig. 36 Fragility functions for the three-story reinforced concrete frame with infills typology (RC1) from the survey form. The fragility functions are derived from expert judgement for different DSs. Solid lines represent the DS fragility function derived based on the opinion of all 40 experts that filled the questionnaire (“All Experts”), while dashed lines are the DS fragility functions derived based only on the opinion of experts with post-earthquake damage assessment experience (“Only DA Exp.”)

expert observations are used to get the probabilities of attaining or exceeding a DS at each PGA value instead of using the structural analysis data.

Figure 35 shows the DS fragility functions for a four-storey URM residential building (type M3-M) which was included in the questionnaire. Additionally, the DS fragility functions were calibrated using the judgement of all experts, as well as the judgement of a subset of experts with experience in post-earthquake damage assessment and/or retrofit. The fragility functions can be seen in Fig. 35 (solid and dashed lines). In case of the M3 building, no significant differences between the two sets of fragility functions were observed.

Figure 36 presents the DS fragility functions for a three-storey reinforced-concrete office building, believed to be a RC1 building type (Table 2). Similarly, as in Fig. 35, the solid and dashed lines represent the fragility functions derived based on the opinion of all experts and the subset of experts with post-earthquake damage assessment experience, respectively. Once again, the difference between the two sets of fragility functions is not significant.

Note that the fragility function for DS4 and DS5 for some of the RC building typologies could not be constructed due to insufficient data generated by expert opinion—most experts believed that a structure would not attain such damage states at any of the considered earthquake intensities.

Expert-based DS fragility functions were compared with the analytically derived fragility functions presented in the European Seismic Risk Model 2020 (ESRM2020) (Romão et al. 2020). Buildings from the survey were classified using the scheme proposed in ESRM2020 by specifying the following attributes: the material and type of the lateral load-resisting system; code level, ductility, and in some cases the lateral force coefficient; and the building height.

It should be noted that the ESRM2020 classifies damage into four DSs, while five DSs were used in this study, as defined by the EMS-98 scale. Therefore, the results were compared only for DS1—Slight Damage for all buildings considered in the questionnaire (Table 7). Both the median and the dispersion values of the expert-based fragility functions were smaller than those proposed in ESRM2020, leading to the conclusion

Table 7 Comparison of DS1—Slight Damage fragility function parameters derived from expert opinion and presented in the European Seismic Risk Model 2020

Building ID	Proposed building typology for Serbia	Fragility function parameters		GEM V3.1 taxonomy string for the Equivalent ESRM2020 Building Type (Romão et al. 2020)	Fragility function parameters	
		μ [PGA in g]	β		μ [PGA in g]	β
1	M4	0.04	0.43	MCF/LWAL + DUL/H:2	0.33	0.53
2	M2	0.02	0.5	MUR/LWAL + DNO/H:1	0.31	0.46
3	RC2	0.05	0.6	CR/LWAL + DUM/H:5	0.54	0.65
4	RC1	0.05	0.48	CR/ LFINF + CDL + LFC:5/H:3	0.3	1.33
5	RC3	0.05	0.63	CR/LWAL + DUL/H:12	1.24	1.15
6	M3	0.02	0.65	MUR/LWAL + DNO/H:4	0.23	0.86
7	RC2	0.04	0.54	CR/LWAL + DUL/H:6	0.42	0.81
8	M2	0.02	0.46	MUR/LWAL + DNO/H:2	0.23	0.61
9	RC3	0.04	0.5	CR/LWAL + DUL/H:10	0.82	1.07
10	M4	0.03	0.47	MCF/LWAL + DUL/H:2	0.33	0.53

that the expert-based estimates of fragility function parameters are more conservative than the analytically derived parameters presented in ESRM2020. It should be noted that the PGA values used to derive expert-based fragility functions are based on the median value of the MCS intensity scale conversion provided by Eq. 1. Furthermore, the comparison assumes that the ESRM2020 definition of DS1 is equivalent to the EMS-98 DS definition used to derive expert-based fragility functions. Finally, as is the case for any expert-based model, this vulnerability model suffers from the limitations imposed by the limited experience and subjectivity of the experts.

7 Conclusion

This paper presents a comprehensive study of the residential building stock in Serbia, including an overview of seismic hazard setting, the building stock, and a proposed classification of the residential building stock. Reported evidence on the performance of common building typologies in past earthquakes in Serbia and the region, as well as collective expert knowledge, served as the basis for developing expert-based seismic fragility functions for common building typologies. The following conclusions were derived based on this study:

1. The territory of Serbia is located in an area of moderate seismic activity. The current seismic hazard map for the 475-year return period earthquake (in compliance with Eurocode 8) shows PGA values in the range from 0.05 g to 0.25 g (for ground type A), while the empirical PGA values were estimated at 0.10–0.14 g range for Belgrade and Novi Sad, the two most populated Serbian cities.
2. Serbia is a relatively small country with a population of 7,186,862, based on the 2011 Census. Approximately 60% of the population lives in urban settlements, while the remaining population occupies suburban and rural areas. For this study, the territory of Serbia was divided into six geographic regions, and relevant indicators related to the residential building stock in each region were analysed. It was observed that urban and rural/suburban dwellings are evenly distributed in major cities. Belgrade, Serbia's capital, houses 23% of the country's population, and is a predominantly urban centre, with 81% of urban dwellings. Previous studies have shown that the majority of residential buildings in Serbia are single-family houses, that is, 57.0% based on the built-up area and 92.1% based on the total number of buildings. Majority of existing dwellings in Serbia were constructed in the period from 1961–1980, based on the first comprehensive Yugoslav seismic design code which was issued in 1964.
3. The authors have proposed a classification of residential buildings in Serbia, based on the review of census data and information related to the national residential building stock from past projects. The buildings were classified into 8 main typologies, based on the material of the Lateral Load-Resisting System (LLRS), i.e., wood (W), masonry (M), and reinforced concrete (RC), and the type of LLRS, i.e., frame, wall, and dual frame-wall system. For the classification of URM buildings, the type of floor diaphragm (rigid or flexible) was also accounted for in the classification. Besides these primary attributes, which were explicitly considered in the classification, two secondary attributes (date of construction and building height), have been implicitly considered. The attributes for the proposed classification were chosen considering their relevance for seismic risk-related studies. Although the code level and the corresponding expected seismic performance/

ductility of buildings were not considered in the classification, they can be implicitly determined based on the date of construction versus the period of enforcement of different seismic design codes.

4. The performance of residential buildings in past earthquakes in Serbia and the neighbouring countries Croatia, Slovenia, Montenegro, North Macedonia, and Bosnia and Herzegovina was reviewed in the paper. These countries were a part of Yugoslavia from 1944–1991 and shared similar construction practices and design codes. Multi-family URM residential buildings experienced severe damage or collapse in the 1963 Skopje, North Macedonia earthquake. URM buildings experienced damage in all subsequent moderately strong earthquakes in the region. In the 2010 Kraljevo, Serbia earthquake many older multi-family URM buildings with rigid floors and RC ring beams experienced repairable structural damage. It was reported that URM buildings with wooden floors were severely damaged in the 2020 earthquakes in Croatia, with the epicentres near Zagreb and Petrinja. Properly constructed confined masonry buildings performed well in past earthquakes in the region. Information related to the performance of RC buildings in past earthquakes is limited. The 1969 Banja Luka earthquakes exposed prefabricated RC buildings to relatively strong ground shaking, but the buildings performed well. In the 1979 Montenegro earthquake, several modern RC buildings (mostly hotels) were severely damaged. The evidence of building performance in past earthquakes in the region is relevant for estimating the seismic vulnerability of the Serbian residential building stock.
5. Examples of building damage from past earthquakes in Serbia and the region, categorized according to the EMS-98 scale, were presented for each building typology defined by the proposed building classification. Furthermore, a survey was conducted to collect expert opinions and construct expert-based fragility functions for building typologies from Serbia. The estimates of potential building damage due to varying earthquake intensities were provided by 40 local structural engineers and were subsequently statistically analysed to calibrate the parameters for fragility functions. The obtained fragility functions were compared to the equivalent fragility functions proposed by the European Seismic Risk Model 2020.

This study is a part of an ongoing seismic risk assessment initiative in Serbia. The proposed classification of residential buildings is the basis for developing an exposure model for Serbia. The expert-based fragility curves developed in this study will serve as the first step towards developing a vulnerability model for the Serbian building stock. The results of the current initiative are going to be used for updating the seismic risk data for Serbia in the European Seismic Risk Model 2020.

Author contributions All authors contributed to the conceptualization of the manuscript. Material preparation, data collection and analysis were performed by SB, NB, MP, and JB. The first draft of the manuscript was written by NB, SB, MP, and BB, and all authors commented on previous versions of the manuscript. All authors have read and approved the final manuscript.

Funding Open access funding provided by Swiss Federal Institute of Technology Zurich. The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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