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Invited Lecture

CLASSIFICATION OF RESIDENTIAL BUILDING STOCK IN SERBIA

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Abstract

Developing a classification system (taxonomy) for buildings is a critical step for seismic risk assessment studies. Such a system can be used to characterize a building portfolio within urban/rural settlements or building stock for the entire country. Serbia is located in a region characterized by a moderate seismic hazard. In the last century, 10 earthquakes of magnitude 5.0 and higher occurred in Serbia, the strongest (M 6.0) in 1922. The strongest earthquake in the 21st century (M_w 5.5), with an epicenter close to Kraljevo, occurred in November 2010 and caused significant damage to residential buildings. In 2019, members of the Serbian Association for Earthquake Engineering (SUZI-SAEE) contributed to the SERA project and its goal to develop a seismic risk model for Europe. A taxonomy of residential buildings in Serbia was developed based on previous national and regional building stock studies. The proposed taxonomy includes the Lateral Load-Resisting System (LLRS) (e.g., wall, frame, dual wall-frame system) and material of the LLRS (e.g., masonry, concrete, wood) as the main attributes. The type of floor diaphragm (rigid or flexible) has been specified only for masonry typologies with unreinforced masonry walls, while building height and date of construction have been implicitly considered. According to the proposed taxonomy, there are 9 residential building typologies in Serbia; out of those, 5 typologies are related to masonry structures, 3 are related to RC structures, and one is related to wood structures. This paper describes the proposed taxonomy and outlines the characteristic features of different building typologies and their relevance for estimating seismic vulnerability and risk. A comparison of the proposed taxonomy for Serbia and published taxonomies for Croatia is also presented.

Keywords: residential buildings, building taxonomy, seismic risk assessment, exposure model

1. Introduction

Seismic risk assessment studies can be performed at different scales (municipal, regional, national, etc.) to estimate potential earthquake-induced losses and identify highly vulnerable assets (e.g., buildings) that may need to be retrofitted as a part of a disaster mitigation initiative. It is well established that seismic risk for a specific building or a building portfolio depends on the corresponding seismic hazard, vulnerability, and exposure. Seismic hazard can be quantified based on a probabilistic estimate of the expected earthquake intensity for a specific location or region, while vulnerability is related to chances of damage and losses for assets exposed to specific hazard levels. Finally, exposure is related to the number, type, and value of assets that are the scope of a specific risk

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assessment study. One of the most comprehensive initiatives focused on developing a seismic risk model for Europe, undertaken under the HORIZON2020 SERA project, used the seismic risk assessment framework originally developed under the Global Earthquake Model (GEM). Serbia participated in the SERA project by sharing information related to the exposure model [1]. This project motivated the members of the Serbian Association for Earthquake Engineering (SUZI-SAEE) to initiate a seismic risk assessment study focused on the Serbian building stock.

The first step towards developing an exposure model consists of developing a building classification system, also known as a building taxonomy. Buildings can be classified in different ways, but in most cases, the selected building characteristics (also known as attributes or facets) which are used to develop a taxonomy are similar, including the material of Lateral Load Resisting System (LLRS) (e.g., masonry, reinforced concrete - RC), type of LLRS (e.g., moment frame, wall system, etc.), and a few other attributes.

A few taxonomies were developed for applications on a global scale. PAGER-STR is a global building taxonomy that classifies buildings into 101 classes and has been organized hierarchically. The main attributes include the material of LLRS, type of LLRS, building height, and type of diaphragm [2]. The most comprehensive global building taxonomy is the GEM Building Taxonomy V2.0 [3, 4], which was developed for seismic risk assessment purposes in the Global Earthquake Model (GEM) framework. The taxonomy is multi-faceted and characterizes buildings through 13 attributes, which could be thought of as a building's genome (DNA), see Fig.1. While some of the GEM Building Taxonomy attributes are the same or similar to those in other taxonomies (e.g., PAGER-STR), it also includes a few unique attributes (e.g., building irregularities, type of occupancy, the position of building within a block, etc.). The taxonomy enables the user to explain each attribute in detail. For example, attribute Material of LLRS (e.g. masonry) can be characterized through "details", such as Material technology (e.g. unreinforced masonry, confined masonry), and Material properties. According to the GEM taxonomy, a building class can be described as a "taxonomy string", which combines the information related to each attribute and the associated detail. A slash sign (/) is used to separate attributes, while a plus sign (+) includes an additional level of detail for a specific attribute. Each attribute and detail have a unique ID. For example, the ID for unreinforced masonry is MUR, the ID for Wall (a type of LLRS) is LWAL, and the ID for building height (number of storeys) is HEX. Therefore, a taxonomy string for a 3-storey loadbearing URM building is /MUR/LWAL/HEX:3/ (the other 10 attributes can be omitted if no information is available). The taxonomy is flexible and enables the user to describe a building class at different granularity (level of detail) as needed. The taxonomy has been widely used for natural hazard and risk assessment via the Open Quake platform [5] and has been expanded into the GED4ALL Building Taxonomy, which includes additional attributes and details required for multi-hazard risk assessment studies [4]. The European seismic risk model developed in the framework of SERA project [6, 7, 8] also used the GEM taxonomy V2.0 to classify European building stock.

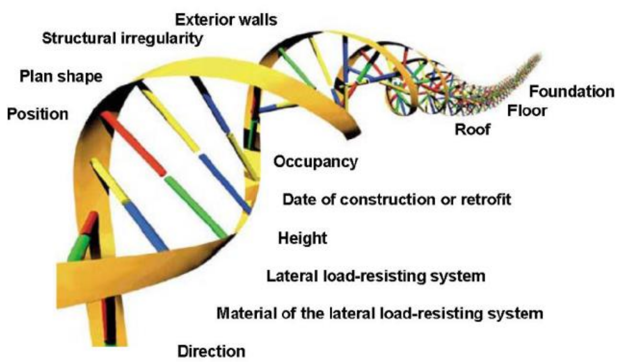

Figure 1. DNA for a building: attributes of the GEM building taxonomy V2.0 [3].

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The EMS-98 Macroseismic Scale [9] also contains a well-known building taxonomy specifically developed for classifying European building stock. According to the EMS-98, buildings have been classified into 15 classes, including 6 RC classes, 7 masonry classes, steel and timber building classes. Each building class has been assigned an expected seismic vulnerability rating, which was empirically determined, but is a valuable reference for seismic vulnerability studies. According to the building taxonomy developed in the framework of the RISK-UE project, buildings were classified into 23 classes depending on the LLRS, construction material, building height, and building design code level [10]. The Syner-G taxonomy was also developed to classify the European building stock. It includes 15 main attributes/facets and can be used to classify buildings in a flexible (non-hierarchical) manner [11].

This paper presents a proposed building taxonomy for Serbia, developed as a part of the SUZI-SAEE study, and compares key features (attributes) for relevant building taxonomies. The paper may be of interest to earthquake engineers and other professionals interested in seismic risk assessment, with a particular focus on the Balkan region.

2. Regional building taxonomies

The authors have also reviewed building taxonomies developed in the region, particularly in the neighbouring countries which were a part of former Yugoslavia. One of the early regional taxonomies was developed in the 1980s as a part of the UNIDO project "Building Construction under Seismic Conditions in the Balkan Region" [12]. The classification was based on the material of LLRS (e.g., masonry, RC), construction technology (e.g., cast-in-situ or prefabricated concrete), and the LLRS (e.g., wall, frame, frame-wall system, etc.). The rapid assessment form developed in this project was used for the damage assessment of buildings affected by the 1990 Gevgelija earthquake in North Macedonia [13]. Classification of buildings in North Macedonia was performed based on a comprehensive building database compiled by IZIIS, Skopje, from 2013-2019 [14]. Masonry buildings were classified into MB (non-earthquake resistant, pre-1964 vintage) and CMB (moderate earthquake-resistant confined masonry buildings, post-1964 vintage). RC buildings (earthquake-resistant, post-1970 vintage) included different LLRSs, e.g. moment frame, dual frame-wall system, RC shear walls, and flat slab systems. A recent seismic loss assessment study for Skopje was based on the inventory of 59,950 buildings classified according to the RISK-UE building taxonomy [15].

Several seismic risk-related projects in Croatia required the development of building taxonomies for major urban centres, such as the capital Zagreb [16]. An initial building taxonomy comprised 14 building classes and was developed for a national seismic risk assessment study [17]. The taxonomy was used for surveying the building inventory in Zagreb. Further studies indicated a need for a more granular classification to reflect the building characteristics better. Hence a more detailed taxonomy, which included 42 building types, was created [18]. The following 4 construction periods were considered: i) PC before 1964 (pre-code), ii) LC from 1964-1981 (low-code), iii) MC from 1981-2005 (medium code), and iv) HC after 2005 (high code, after Eurocode 8 was adopted). A separate project was focused on Osijek, the fourth largest city in Croatia, resulting in a custom building taxonomy for exposure model development purposes. This taxonomy included 15 prevailing building types and was used for a field survey of 1100 local buildings [19].

A few seismic risk assessment studies in Bosnia and Herzegovina required the classification of building portfolios. A seismic risk assessment study was performed in Tuzla, the third-largest city in the country [20]. In total, 203 RC and masonry buildings were surveyed. RISK-UE building taxonomy was used for structural and typological characterization of the buildings. An ongoing research study in Sarajevo, the country's capital, focuses on developing a database of 700 structures in two selected municipalities as the starting point for developing a national building taxonomy [21].

A recent scenario-based risk assessment study in Slovenia [22] used building data contained in the Real Estate Register, which contains information related to building units, including the year of construction, occupancy, built-up floor area, the material of the LLRS, building value based on the appraisal, number of storeys, and building height.

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A summary of relevant international building taxonomies and national/local taxonomies for the neighbouring countries has been presented in Table 1. The table identifies key building attributes, which are intended to differentiate between seismic vulnerabilities associated with different building typologies for seismic risk assessment purposes.

Table 1 – International and national building taxonomies: a summary of attributes

		International taxonomies			**National taxonomies**			
	Attributes	**GEM V2.0**	**RISK -UE**	**EMS-98**	**Croatia-Zagreb**	**Croatia-Osijek**	**North Macedonia**	**Slovenia**
		[3]	**[10]**	**[9]**	**[18]**	**[19]**	**[14, 15]**	**[22]**
1	Material of the LLRS	✓	✓	✓	✓	✓	✓	✓
2	Type of LLRS	✓	✓	✓	✓	✓	✓	✓
3	Building height	✓	✓		✓	✓	✓	✓
4	Date of construction	✓			✓	✓		✓
5	Seismic code level	**E**[1]		**E**[2]	**E**	**I**	**I**	**I**
6	Occupancy (function)	✓				✓		
7	Structural irregularity	✓	✓		✓	✓		
8	Material of exterior walls	✓				✓		
9	Roof type	✓						
10	Floor type	✓			✓	✓		
	Other attributes	Direction; building position within a block; shape of the building plan; foundation		Material technology (masonry);	Material technology (masonry); wall layout; hybrid LLRS	Building condition; building size; floor area; built-up area; soil type		
	Total number of typologies	Very large	23	13	42	12	7	14

Notes: 1-included only in the GED4ALL taxonomy; 2-only for RC structures; E- explicitly stated in the classification; I- implicit (can be deducted based on the period of construction)

It can be seen from Table 1 that all taxonomies have at least two attributes: the material of the LLRS and the type of LLRS. The most detailed international taxonomy is GEM V2.0, since it can characterize many building typologies due to a large number of attributes and details (secondary attributes). Among the national typologies developed in the neighbouring countries, the most detailed ones are from Croatia. The taxonomy developed for the Zagreb study [18] describes building features characteristic of local construction practices.

3. Proposed classification of residential buildings in Serbia

3.1 Background

Previous research studies on the Serbian building stock were mainly based on the review of the building stock of various European countries. The most relevant project for the current study is the

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TABULA project (2009-2012), a European project co-founded by Intelligent Energy Europe [23]. 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 participating in the project: a taxonomy in the predetermined TABULA form and a national one. Both taxonomies classified residential buildings based on the year of construction and the building type. The TABULA taxonomy divided buildings into single-family houses, terraced houses, multifamily houses, and apartment blocks. The national building taxonomy for Serbia is more complex, categorizing the buildings into six types. Single-family housing was classified into freestanding houses and houses in a row, while multifamily housing was categorized into freestanding buildings, lamella (housing block), buildings in a row, and high-rise buildings. Each typology was described in detail on an example (building archetype) and included a description of the structural system and horizontal and vertical structural elements. The TABULA project also offered an insight into the built-up area and the 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 estimated number of buildings). Also, it was concluded that most freestanding single-family houses were built from 1971 to 1980. The TABULA project deliverables prepared by the Serbian team [23-25] were important resources for the present study. The only previous study related to Serbian building classification for seismic risk assessment purposes was reported by Radovanović and Petronijević [26]. The authors applied the EMS-98 scale to identify common building typologies in Serbia and concluded that seven EMS-98 typologies (5 masonry typologies and two RC typologies) are sufficient for characterizing building stock in Serbia.

A review of previous studies on the residential building stock revealed a need to develop a novel classification of residential buildings in Serbia, which is presented in Table 2. The presented building classification comprises 9 building typologies, including 5 masonry typologies (M), 3 reinforced concrete (RC) typologies, and a wood typology (W). Each building typology is described using an alphanumeric ID, name, and primary and secondary taxonomy attributes, as shown in the table. The primary attributes which are used to describe building types include Lateral Load-Resisting System (LLRS), e.g., wall, frame, dual wall-frame system; material of the LLRS (e.g., masonry, concrete, wood), and floor diaphragm type (rigid or flexible). Unreinforced masonry (URM) buildings with flexible diaphragms (building types M1, M2) are more vulnerable to earthquake shaking when compared to URM buildings with rigid diaphragms, as demonstrated by numerous surveys and studies. Flexible diaphragms may cause large lateral displacements and the out-of-plane toppling of the walls in the weak direction (normal to the earthquake action), which reduces the building integrity and prevents the walls from acting together as a box (box action). Building height is also an important attribute to consider for M3 building type (URM buildings with rigid diaphragms). Based on the number of floors, this typology was further subdivided into single- and multifamily building types (M3-S and M3-M). The secondary attributes include building height and period of construction. Building height is related to the dynamic characteristics of a structure, whereas the year of construction can be related to the seismic code level to which the building was designed.

A detailed description of masonry and RC building typologies is presented in the following sections. Since wooden buildings represent only a tiny fraction of Serbia's residential building stock, they have been omitted from this paper.

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Table 2 – Proposed classification of residential buildings in Serbia

ID	Building typology	Primary attributes			Secondary attributes
		Material	LLRS	Type of roof/floor diaphragm	
(1)	(2)	(3)	(4)	(5)	(6)
M1	Unreinforced earthen or stone masonry walls with flexible diaphragms	Masonry	**LLRS:** Wall (constructed using stone masonry, rammed earth, or load-bearing adobe brick masonry)	Flexible (wooden structure)	**Height:** 1-2 floors **Date of construction:** before 1945
M2	Unreinforced masonry walls with flexible diaphragms	Masonry	**LLRS:** Wall (constructed using solid clay bricks in low-strength mortar)	Floor: flexible (wooden structure or Prussian vault) Roof: flexible (sloped wooden structure)	**Height:** 1-4 floors **Date of construction:** before 1960
M3	Unreinforced masonry walls with rigid diaphragms	Masonry	**M3-S (single-family) LLRS:** Wall (constructed using modular clay blocks in cement mortar)	Floor: rigid (semi-prefabricated concrete and clay floor system) Roof: flexible (sloped wooden structure)	**Height:** 1-2 floors **Date of construction:** 1960-present
	Unreinforced masonry walls with rigid diaphragms	Masonry	**M3-M (multifamily) LLRS:** Wall (constructed using solid clay bricks in cement mortar)	Floor: rigid (semi-prefabricated ribbed RC floor or composite RC&clay floor) Roof: rigid (flat RC slab) or flexible (sloped wooden structure)	**Height:** 3-6 floors **Date of construction:** 1920-1970
M4	Confined masonry buildings	Masonry	**LLRS:** Wall (constructed using modular clay blocks in cement mortar)	Rigid (semi-prefabricated RC or composite concrete and clay system)	**Height:** 1-5 floors **Date of construction:** 1970-present
RC1	RC frames (cast in-situ) with masonry infills	Reinforced concrete (RC)	**LLRS:** RC frame with masonry infills built using solid clay bricks or modular clay blocks	Rigid (semi-prefabricated RC or composite concrete and clay floor system)	**Height:** 4-10 floors **Date of construction:** 1960-present
RC2	RC walls (cast in-situ) or dual frame-wall system	Reinforced concrete (RC)	**LLRS:** Wall (although a frame may resist a small fraction of seismic load)	Rigid (solid RC slab)	**Height:** 5-15 floors **Date of construction:** 1960-present
RC3	Prefabricated RC buildings	Reinforced concrete (RC)	**LLRS:** Wall (large panel buildings), or dual frame-wall system	Rigid (prefabricated RC slab)	**Height:** 6-15 floors **Date of construction:** 1960-1990

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3.2 Masonry building typologies

The proposed classification includes 4 basic masonry typologies (M1 to M4). Typology M3 is subdivided into two subtypes (M3-S and M3-M), see Table 2. Masonry typologies denoted by M1, M2, and M3 characterize older, unreinforced masonry (URM) buildings, whereas typology M4 characterizes confined masonry buildings of more recent construction.

Buildings classified as M1 and M2 typologies have wooden floors which act as flexible diaphragms, and they were predominantly used in Serbia until the end of WWI. Floor systems in buildings classified as M3 or M4 typologies can be treated as rigid diaphragms, but there are a few types, depending on the construction period. The application of ribbed RC floors started at the beginning of the 20th century. A semi-prefabricated ribbed RC floor system (Herbst), consisting of 25 cm deep prefabricated RC ribs and a cast-in-situ concrete layer, was practiced until the end of WWII. Avramenko is another semi-prefabricated floor system that has been used since the 1930s. A shift towards semi-prefabricated concrete and clay floor system happened during the mid-1960s. For example, LMT (light prefabricated floor) is a semi-prefabricated floor system consisting of cast-in-situ RC joists placed between masonry elements. Since mid-20th century, solid RC slabs have been used in multi-story masonry and RC buildings. Examples of masonry building typologies are presented in Fig. 2, and a brief description of each typology is presented in this section.

a) b) c) d)

Figure 2. Examples of masonry building typologies from Serbia: a) M1- a single-family building in Irig (Vojvodina); b) M2 – an early 20th century URM building in Zemun; c) M3-M – an apartment building in Belgrade; d) M4- a single-family house under construction, Zlatibor.

M1: Unreinforced earthen or stone masonry walls with flexible diaphragms

Earthen construction and adobe masonry were common for residential buildings of M1 building type, whereas stone masonry was primarily used for public buildings, fortresses, churches, etc. Houses of earthen construction were common in Vojvodina from the 18th century until the first half of the 20th century, mainly in the form of low-rise (one-story) single-family houses with walls constructed using rammed earth technology (called *naboj* in Serbia). These buildings are characterized by rectangular or L-shaped plans, and the wall thickness is 50 cm or higher. Adobe masonry, characterized by walls constructed using unburnt clay bricks in mud mortar, was more common in urban construction. These buildings had wooden floors and roofs and usually had two-floor levels. Historic urban centres in Vojvodina have many examples of such buildings, some of which were recognized as heritage structures in the city of Novi Sad.

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Stone masonry was rarely used in the construction of single-family residential buildings in Serbia; however, large residential buildings with foundations, basement walls, and/or load-bearing walls made of stone masonry were constructed in Belgrade in the 1870s. Several tower-like dwellings dating from the 19th century were also constructed using stone masonry in rural areas near Dečani Monastery in Kosovo and Metohija. Such buildings feature wooden floors, a square plan shape, and thick walls with a few windows.

M2: Unreinforced masonry walls with flexible diaphragms

This building typology was common in urban regions of Serbia during the 19th century and the first half of the 20th century. These buildings usually have 1 to 4 floors and were used as single-family or multi–family residential buildings (depending on the building height and economic status of the owners). The key feature of these buildings is the use of fired (burnt) solid clay bricks for the first time in Serbia. The first brick manufacturing facilities in Serbia were established in the second half of the 19th century, which enabled wider use of brick masonry construction. The 1896 building Act for the Town of Belgrade restricted the use of timber and dictated standard dimensions for clay bricks as a common material for wall construction [27]. The prescribed wall thickness reduced over time, ranging from 45 - 60 cm before 1933 to 25-51 cm after 1933. Lime mortar was used for masonry construction until the end of WWII. Wooden floors with 14 cm x 20 cm beams at 80 cm spacing and 2.5 cm thick wooden planks were typically used on upper floors, while suspended floors above the basement and ground floor levels were usually constructed as a jack arch system (Prussian vault), consisting of shallow brick vaults spanning between the iron beams. These buildings have sloped wooden roofs with clay tiles.

M3: Unreinforced masonry walls with rigid diaphragms

This building typology has been widely used both in urban and rural regions of Serbia. They are characterized by rigid floor diaphragms. This typology can be subdivided into M3-S and M3-M typologies based on the building height and masonry technology. Typology M3-S is related to low-rise single-family residential houses with load-bearing walls constructed of modular (multi-perforated) clay blocks or solid clay bricks bonded by cement:lime:sand mortar. Wall thickness is influenced by building height and type of masonry element (solid brick or modular block), and it usually ranges from 19 cm to 38 cm. These buildings have sloped wooden roofs and clay tiles. Construction of these buildings started in the 1960s and continues to date, mostly in the parts of the country where construction of confined masonry (M4-type) is not mandatory.

M3-M typology is related to multifamily apartment buildings with load-bearing masonry walls constructed of solid clay bricks and cement:lime:sand mortar. These are mid-rise buildings (with 3-6 floors) and have regular plans and elevations with symmetrical wall layouts. The thickness of interior walls ranges from 25 cm to 30 cm, whereas exterior walls are usually 38-51 cm thick. This type of construction was practiced from the end of WWII until the beginning of the 1970s. The buildings constructed in the period 1950-1970 have horizontal RC ring beams at floor/roof levels, but they do not have vertical RC confining elements, which are present in confined masonry construction. These buildings usually have flat roofs (the same construction as floors). A detailed description of typical M3-M buildings from Serbia and their seismic performance can be found elsewhere [28].

M4: Confined masonry buildings

The first Yugoslav seismic design code, issued in 1964, contained provisions on horizontal and vertical RC confining elements in masonry buildings, which are characteristic of modern confined masonry construction currently practiced in Serbia. The code prescribed building height limits depending on the seismic hazard level and other criteria, as summarized in [29]. These are low-rise residential buildings, typically 1-4 floors high. Masonry walls in these buildings are constructed using modular (multi-perforated) clay blocks, which superseded the use of solid clay bricks in the 1970s [30]. Due to the use of modular blocks, wall thickness has been reduced to 19-25 cm. These buildings have rigid floor diaphragms, usually with semi-prefabricated floor systems. Flat RC and sloped wooden roofs are typical for multifamily and single-family buildings.

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Although confined masonry technology is widely used in Serbia, it is not always easy to distinguish buildings of M4 typology from RC frames with masonry infills (RC1) in field surveys of existing buildings. Similarly, identifying vertical RC confining elements in existing buildings is often challenging. Hence it is possible to wrongly classify buildings that could be potentially classified either as M3 or M4 buildings. The use of thermal imaging has proven to be helpful in identifying RC elements in field surveys of RC and masonry buildings [31].

3.3 Reinforced concrete building typologies

RC buildings were classified into three typologies. Two out of three RC typologies are associated with cast-in-situ concrete construction technology (RC1 and RC2), while the third is associated with prefabricated RC construction (RC3). Construction of RC residential buildings in Serbia started after WWII, and is limited primarily to multifamily residential buildings. Initially, RC1 building typology was popular, but since the 1960s, most RC buildings have at least a central (elevator) core and additional structural walls (RC2 systems). Prefabricated RC technology (RC3 typology) was widespread in urban areas of former Yugoslavia, including Serbia, from the late 1950s until the early 1990s. Prefabricated RC systems were not used after the dissolution of Yugoslavia; hence dual wall-frame system (RC2 typology) remains the only RC system used in multifamily residential building construction. Recent RC construction features RC walls and flat slab frames acting as a gravity load-resisting system. Examples of RC building typologies are presented in Fig. 3, and a brief description of each typology is presented in this section.

a) b) c)

Figure 3. Examples of RC building typologies from Belgrade, Serbia: a) RC1 - original office of "Energoprojekt" consulting firm; b) RC2 – a multifamily residential building [25] and c) RC3 – high-rise prefabricated large panel RC buildings, New Belgrade

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

Construction of the first cast-in-situ RC frame buildings dates back to the late 1930s; however, construction of such buildings for residential purposes was more common after the end of WWII, due to the migration of the population to urban regions and post-war rebuilding efforts [25]. These were mid-rise buildings (up to 10 floors high) and usually had a regular plan shape; however, there was often an open space on the ground floor used for commercial purposes. Until the 1970s, stiff infills (solid clay brick masonry walls) were used, but they later changed to modular clay blocks and, in some cases, precast concrete panels for exterior infills. In the initial period, cast-in-situ ribbed RC floor system was used, but it was later replaced by cast-in-situ RC flat slabs. The typical foundation system for RC buildings was strip footings, whereas mat foundations were used in buildings with underground floors. Growing market needs and the introduction of the first seismic design codes in 1964 led to the construction of buildings with dual RC frame-wall systems (RC2) and prefabricated RC buildings (RC3), which entirely replaced the RC1 typology.

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

RC wall system was introduced after WWII, consisting of structural RC walls that resist lateral and gravity walls in RC buildings. This system became more common in the late 1950s with the

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application of the slip-form construction method for high-rise buildings (more than 10 floors high). During the same period, the tunnel-form method was used to construct high-rise buildings with elongated plan shapes. These buildings have a central core and regularly spaced structural walls with the same thickness along the building height. The dual wall-frame system, in which lateral loads are resisted both by the structural walls and the frames, was more widely used after 1964, when the first seismic design code was issued.

RC3: Prefabricated RC buildings

Construction of prefabricated RC buildings started in the 1950s in former Yugoslavia, Eastern European countries, and the Soviet Union. More than 15 prefabricated construction technologies were developed in the former Yugoslavia, including the IMS Building System, Trudbenik, Yugomont YU-61, etc. [32]. Large panel systems, consisting of RC wall and floor panels, were particularly popular. These elements were prefabricated, transported, and joined together at the construction sites. After erecting in the final position, structural elements were connected via welded steel connections and/or cast-in-situ grouted concrete. French large panel system Balency was modified by the Belgrade-based engineering firm “Rad” into the “Rad-Balency” system, which was used for the construction of high-rise buildings (6-15 floors), many of which exist in Belgrade and other urban regions [33]. The IMS Building System, developed by Prof. Branko Žeželj at the Institute IMS in Belgrade and used in other parts of former Yugoslavia, consisted of prefabricated RC columns, waffle slabs, and edge girders. Columns and slabs were joined together at each floor level by post-tensioning in two orthogonal horizontal directions. It was a dual frame-wall system that included cast-in-situ RC shear walls. The system was used to construct mid- and high-rise buildings (6-20 floors) [34].

4. Conclusions

The paper presents a classification (taxonomy) of residential buildings in Serbia, which has been proposed by the authors. According to the taxonomy, there are 9 prevalent building typologies, including 5 typologies related to masonry buildings, 3 typologies related to RC buildings, and a typology related to wooden buildings. This initial taxonomy is based on reviewing previous studies related to the building stock in Serbia and a survey of experts, which resulted in developing seismic fragility curves for typical buildings [35]. A comparison with the building taxonomies from neighbouring countries with similar construction practices and design codes points to numerous similarities in the attributes and the main building typologies. It is expected that the taxonomy will be further developed with a higher level of granularity after future field surveys of typical buildings. The proposed taxonomy will be used to develop an exposure model for Serbia and future seismic risk assessment studies.

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