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PREFABRICATED REINFORCED CONCRETE RESIDENTIAL BUILDINGS: A FOCUS ON THE JUGOMONT SYSTEM

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Abstract

The second half of the 20th century was marked by the rise of prefabricated concrete systems used as the best solution for fast construction after the vast devastation of the building stock after WWII. In Yugoslavia, several innovative structural systems were used for mass construction of multi-family housing blocks. Two large groups of prefabricated systems were: 1) large panel and 2) dual frame-wall systems. Some of these systems were adapted from other European countries by local construction companies, such as Rad-Balency, but over time engineers developed new ones, the most famous being the IMS building system developed by Professor Branko Žeželj at the Institute IMS in Belgrade. A construction boom from 1964-1980 brought new urban projects and developments, such as Novi Beograd (New Belgrade) in Serbia, Novi Zagreb (New Zagreb) and Split 3 in Croatia, Nova Gorica in Slovenia, and the reconstruction of Skopje, North Macedonia after the 1963 earthquake. This paper presents a case study on Blok 28 building complex in New Belgrade, the largest urban development in Serbia and former Yugoslavia and a polygon for experiments in architecture and construction technologies. Architectural and structural features of the Jugomont prefabricated reinforced concrete system are outlined in the paper, with a focus on the features that influence the seismic performance of buildings constructed using this system and the failure mechanisms of prefabricated wall structures composed of panels and their connections under seismic actions. The paper is expected to contribute towards the understanding of the architectural and structural design concepts related to prefabricated reinforced concrete buildings which are a part of the existing building stock in urban areas of the countries within the territory of former Yugoslavia.

Keywords: prefabricated reinforced concrete panels, seismic behaviour, failure mechanisms, mid-20th century heritage, New Belgrade, Jugomont

1. Introduction

The objective of this paper is to analyse the mid-20th-century building stock in the Western Balkans and to discuss the architectural and structural aspects of prefabricated multi-family housing built during this period. Most of these structures were built between the 1960s and 1980s with the idea of increasing the building stock in major cities in former Yugoslavian republics. They stand as vital examples of the region's heritage and were recognised internationally, and presented in 2018 at the Museum of Modern Art in New York as part of the exhibition *Toward a Concrete Utopia: Architecture in Yugoslavia, 1948 -1980* [1]. These buildings are examples of modernist architectural and engineering achievements and need to be preserved and rehabilitated.

The increasing need for housing in the post-war Yugoslavia, led architects and engineers to develop prefabricated systems due to ease of production of elements off the construction site and fast assembly. These structures reflect the relationship between modernist design principles and the socio-political context of the time. This paper focuses on residential multi-family buildings built using reinforced concrete (RC) panel elements in the Jugomont system.

This paper presents an overview of housing construction practices in the second half of the 20th century in Yugoslavia, focusing on prefabricated multi-family housing, its characteristics, external influences and the seismic characteristics of the structures. A typical residential community in New Belgrade, Serbia, Block 28, was selected for this study since it features the buildings constructed in the Jugomont system, which was developed in Croatia. The paper showcases the diversity of architectural and engineering solutions for that period and the seismic vulnerability of these buildings.

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Recent earthquakes in the Western Balkans and the neighbouring region, that is, the November 26, 2019 Durres, Albania earthquake (M 6.4) and the March 22, 2020 Zagreb, Croatia earthquake (Mw 5.4), highlighted the seismic vulnerability of urban building stock. Lessons from these earthquakes provided valuable insight into the seismic performance of the affected building typologies. Prefabricated RC buildings in urban centres of Albania were exposed to the earthquake but exhibited relatively minor damage compared to cast in-situ RC frame buildings and unreinforced masonry buildings, demonstrating the resilience of these systems under moderate seismic actions [2, 3]. The buildings affected by the 2020 Zagreb earthquake were mostly older unreinforced masonry structures, which are not the subject of this paper (note that prefabricated RC buildings were not affected by the earthquake).

The aim of this paper is to provide an overview of architectural and structural design concepts of post-WWII urban construction in former Yugoslavia, with a focus on prefabricated RC construction practices. Specifically, the focus is on the Jugomont system, which was developed in Zagreb, Croatia, and was applied throughout the region. Key structural elements and their connections were described in the context of identifying possible seismic failure mechanisms of buildings constructed using the system and the consequences on the seismic performance of these buildings.

2. Building Context in Post-War Yugoslavia

The post-World War II period in Europe was marked by the (re)construction of damaged cities and the design of new city centres. Urban planning relied on modernist principles outlined in the Athens Charter during the 1933 CIAM meeting. Based on architect Le Corbusier's concept of the Radiant City—"a city of sunlight, space, and greenery" [4]—new urban plans required vast areas to implement large-scale interventions with varied functions aligned with emerging state ideologies. A product of the CIAM meeting, which involved participation from over half of Europe's nations, was the concept of the *functional city*. The meeting showcased plans for 33 cities, including Zagreb.

The functional city concept was founded around four essential activities—housing, work, recreation, and transportation—and their comprehensive integration into new urban plans [5]. In former Yugoslavia, encompassing six current Balkan countries, the development of Belgrade as the country's capital exemplified the planning and construction of a new urban area guided by these principles. The planning of New Belgrade, located on the left bank of the Sava River, drew from modernist legacies but was adapted to political ideologies. Early plans for New Belgrade were abandoned when Yugoslavia distanced itself from other Eastern European socialist countries and pivoted towards Western Europe. Between 1950 and 1960, the focus shifted from governance-related urban design to addressing housing issues. The ideas of broad roads and buildings surrounded by ample green spaces were retained, and the construction of several public facilities such as the Central Committee building, Federal Executive Council palace and hotel "Yugoslavia" began. Numerous architectural competitions based on the initial plan for New Belgrade attracted architects from across Yugoslavia, resulting in "the creation of a new architectural discourse and architectural-urban planning practice of the new Yugoslavia" [6]. New Belgrade bears witness to the collaboration between architects and engineers in constructing numerous residential buildings that reflect a cohesive post-war architectural language in Yugoslavia.

After WWII, Belgrade saw an influx of new residents who needed housing. Urban planning aimed to make Belgrade a city of millions, though the ideal of "free housing for all" proved unfeasible. Construction technology struggled to keep pace with rapid population growth. The drive for rapid and cost-effective construction led to the development of more than 20 prefabrication systems, which gradually dominated residential construction across Yugoslavia. Housing quality was defined not only by its commodification but also by its functional value [7]. Notable prefabricated systems include the IMS system developed in 1957 and various forms of panel systems, such as Jugomont, Rad-Balency, etc. Prefabricated elements were often combined with cast in-situ RC components such as walls and foundations.

Due to a unified housing policy, residential buildings across Yugoslavia utilised similar or identical prefabricated systems and construction technologies in general. The first five-year construction plan prioritised urbanisation in Belgrade, Ljubljana, and Titograd (now Podgorica) [8]. Major modernisation

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efforts between 1950 and 1960 focused on New Belgrade (Serbia), New Zagreb (Croatia), and Nova Gorica (Slovenia), alongside new industrial centres nationwide. The 1970s saw Split's expansion and the development of Skopje's reconstruction after the earthquake in 1963. "The modernism inherited from the pre-WWII period was a solid foundation, but implementing large-scale mass urbanisation required new knowledge, such as urban development management, construction process organisation, and prefabricated mass production. This knowledge was less about aesthetics and more about broader modernisation, while socialist urbanisation aimed to reduce societal disparities across the region" [9]. The aim was to construct buildings economically, using prefabrication that was simple to produce and could be completed at a faster pace compared to traditional cast in-situ construction practices.

To maximise the number of apartments within a short time, the building designs included mostly two-bedroom apartments. The architects provided design solutions with expanded dining rooms that could accommodate a bed if needed. This approach enabled economical social housing construction for a larger population [10]. Limited construction technology and a shortage of skilled labour necessitated innovative structural solutions tailored to the context. In New Belgrade, the challenges of building on marshland, including the high cost of pile foundations, led to structural innovations aimed at reducing construction weight while ensuring simplicity and cost-effectiveness [11]. The prestressed concrete prefabricated spatial frame system, developed at the IMS institute by engineer Branko Žeželj, was tested during the construction of Blocks 1 and 2 in New Belgrade. Remarkably, Žeželj consulted architects to determine optimal spans for residential design, leading to the adoption of a 4.2x4.2m module which was compatible with available site equipment. Cranes of the time could lift slabs up to 17 square meters, earning the nickname "crane architecture" for post-war construction [11].

The synthesis of architectural and engineering expertise—architects trained at leading European modernist schools and civil engineers implementing contemporary construction systems—placed Yugoslav projects on the 20th-century architectural map alongside major European countries. However, the unique context of Yugoslavia's housing policy and construction produced distinctive architecture and unparalleled mass housing. Prefabricated systems accommodated architectural designs by modifying elements on-site, resulting in a unique architectural style [12]. Despite architects striving to align designs to accommodate the use of prefabricated systems, the government prevented monopolies by ensuring that multiple companies participated in the construction, leading to a predominance of hybrid systems. While this hindered the economic efficiency of mass production, it contributed to unique architectural outcomes. "A region as a space of authentic architectural imagination, which is still to be inscribed on the international map of modernity" [9].

The cultural, social, and political context, combined with technological advancements, shaped the architectural expression of structures where their structural form became prominent. Studies translated and published in numerous journals of the period, including *Tehnika*, *Arhitektura Urbanizam Beograda*, *Arhitektura Urbanizam*, and internal publications by the Urban Planning Institute and Construction Centre provided architects and engineers with a broad knowledge base for designing structures aligned with state policies promoting progress. Ideas for large-scale urban plans, individual buildings, and innovative construction techniques showcased fairs and competitions that raised public awareness of construction and state development. Although urbanisation was not fully realised, the constructed legacy of that period represents a significant 20th-century architectural heritage that remains present in contemporary architectural contexts.

3. New Belgrade Central Zone – Block 28

The central zone of New Belgrade comprises nine blocks, with a central axis of three blocks with public buildings oriented towards the Federal Executive Council building on the north side and a proposed Central railway station on the south side. Designed as an urbanistic entity, this zone draws inspiration from Le Corbusier's city plans. The corner blocks, numbered 21, 23, 28, and 30, feature high towers at their corners, enclosing the central zone. The axis towards the Federal Executive Council building houses compact business districts and public areas, surrounded by 12 high towers. The buildings in the neighbouring blocks around the central axis provide shelter in the interior of the block for its inhabitants

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(Fig. 1). Each block in the central zone is a harmonious blend of typologies, including high-rise buildings, mid-rise residential buildings called lamellae, and public buildings like schools, kindergartens and local community buildings.

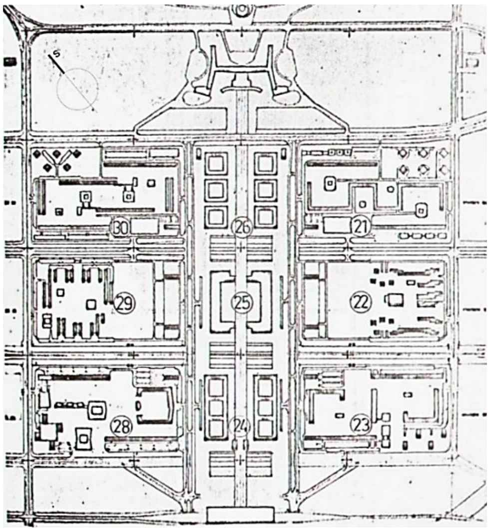

Figure 1. New Belgrade Central Zone (Blocks 21 to 30) with Federal Executive Council building in the northeast [11]

The central zone blocks on the axis (24, 25 and 26) were never fully realised as designed. The idea was to build a new centre equivalent to the historical city centre of Belgrade, but the project primarily focused on constructing apartment buildings and supporting public facilities. Nevertheless, the blocks located along the perimeter of the central zone stand as a witness to this project.

Each block in the central zone of New Belgrade was developed following an architectural competition, which resulted in a diverse array of individual designs for both the block and its buildings. Since the monopoly of companies was prohibited, multiple prefabricated systems, both in terms of construction methods and architectural elements, were implemented. This resulted in unique designs that distinguished each block and left a lasting impact on the modernist architectural heritage.

In this paper, Block 28 will be discussed in detail, specifically in terms of structural design and the application of the Jugomont prefabricated panels. The detailed urban design of Block 28 was proposed based on the design conception for the New Belgrade central zone. The design envisioned nine buildings in total (labelled 1 to 9, see Fig.2), aligning with the planned dynamics for other blocks. Public buildings, including a community council, kindergarten, and school, were strategically positioned in the central area to ensure equal accessibility for all residents (Fig. 3) [14, 15, 16]. Along the perimeter of the block, two long 10-storey buildings (lamellae, numbered 1 and 6) were positioned parallel to the main boulevards. In the western corner, the design envisioned four 16-storey high-rise buildings enclosing the central zone blocks (number 4). Notably, the design proposed a truly unique 4-storey building in the area (number 7), located along the central zone axis, called "Potkovica" (en. horseshoe) for its horseshoe-like shape in plan. The concept behind this shape was to create a barrier towards the public blocks and provide a more private space for the inhabitants of Block 28.

The Block 28 established itself as Yugoslav. The urban concept was set in Belgrade; a team from Ljubljana won the design competition for the block, the prefabricated systems were the IMS system from Belgrade and the Jugomont system from Zagreb, and the contractor was "Hidrogradnja" from Čačak. The success of the project depended on all participants. The constant presence of the investor "Jingrap" played a crucial role in coordinating the construction of the buildings in the block. Communication between the urban planners and the designers of individual buildings, who served as a link with the contractor, resulted in turning all the ideas into reality [14]. This block presents a true

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collaboration of all participants in the project and reflects the idea of the collaboration between architectural design and prefabricated construction technologies [16].

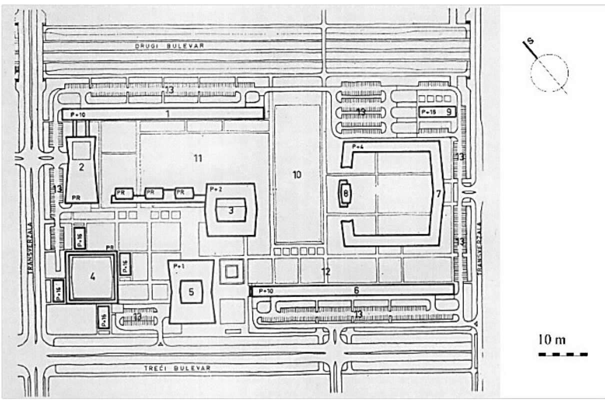

Figure 2. Plan of Block 28, New Belgrade [15]

Figure 3. A 3D view of Block 28 [17]

The architectural and structural design of the “Potkovica” building in Block 28 makes it an important one to date. The unique shape of the building and its construction from the prefabricated system Jugomont demand special attention in architectural heritage. Built in the period from 1969 to 1971 and designed by the architect Ilija Arnautović, the building consists of 24 modules, creating a zig-zag contour on its facade. The design resembled a block of terraced houses and created a more human-scale building. The building has four floors, with four apartment types, the largest one being a two-bedroom apartment with an area of 81.87 m^2. A typical floor for one module of the building had two of these apartments in mirror with a vertical communication in between [15]. The Jugomont prefabricated system was chosen for this building because of the 3,60 m span, which was convenient for this type of apartment. The typical floor plan of the apartment (Fig. 4), clearly shows that each bedroom has a 3.60 m span, as well as the living room and the kitchen/dining room/bathroom area. Another advantage of the Jugomont system was the adaptability to the building shape. [18] The building façade was also designed using the Jugomont prefabricated panel elements, leaving the connections visible and a natural treatment of the surface – flat or washed concrete. The façade elements changed between closed elements and the ones with openings for windows or balcony doors. The terraces were made as separate elements, seemingly only leaning onto the main structure (Fig. 5).

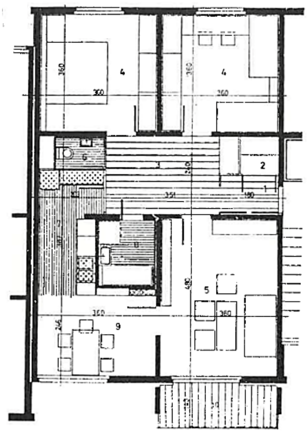

Figure 4. Apartment floor plan.

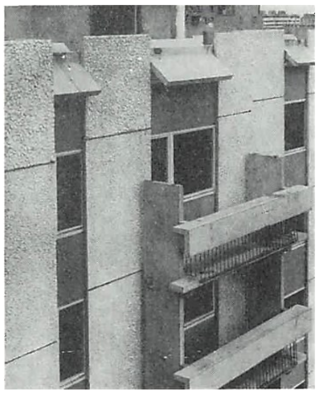

Figure 5. An exterior view of the façade.

According to the architect Ilija Arnautović, the architecture of Block 28 was enriched by using prefabrication systems (contrary to popular opinion). This project could only be completed through constant collaboration of all participants. The “Potkovica” building is a prime example of how, at the

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same time, prefabricated systems can be flexible and adaptable to the urban and architectural design of buildings [18].

4. Jugomont system: a structural and seismic engineering perspective

4.1. Introduction

Use the decimal system for headings with no more than three levels. Jugomont semi-prefabricated large panel system was originally developed in 1959 (JU-59 system), and it further evolved through its variants developed in 1960 (JU-60), 1961 (JU-61), and 1971 (JU-71). The system was named after a Zagreb-based engineering firm, which was established in 1955. The main structural components of the system were prefabricated RC wall and floor panels, which were interconnected along the horizontal and vertical joints. The buildings had cast-in-situ strip foundations. Information related to the Jugomont system and its applications is available in local technical literature dating back to 1960s and 1970s [19].

The Jugomont system was used for construction of mid-rise residential buildings throughout former Yugoslavia. Most buildings were 5-storey high (P+4), which was a common building height for residential buildings at the time when these buildings were constructed (the 1960s and 1970s); however, building height was also limited by structural features of the system, especially for the JU-59 and JU-60 variants. Taller buildings were constructed in the JU-61 system - for example, 6-storey buildings were constructed in Maribor, Slovenia, in 1964 [20], and the system was suitable for the construction of buildings of up to 8-storey height [15].

Plan dimensions of these buildings varied depending on the project and variant of the system. Plan shape was usually regular (rectangular), with a fixed width (approximately 10 m), while the length ranged from approximately 40 m (JU-60) to 77 m (JU-61) [21]. In the case of buildings where architectural design envisaged an irregular shape, buildings were separated into regular blocks by means of construction joints (seismic gaps), e.g., “Potkovica” building, Blok 28, New Belgrade, Serbia [15].

The layout of structural walls in a building, which is very important from the perspective of its response to seismic actions, also evolved over time and varied depending on the variant of the system. The JU-59 variant had only transverse structural walls, while the JU-60 variant comprised of transverse walls plus a single interior longitudinal wall [15]. Finally, the JU-61 variant comprised of transverse walls plus two interior longitudinal walls.

4.2. Key building components and their connections

Sizes of panel elements varied over time, but the objective was to arrange the panels to match the basic cell (room) size (4 m x 4 m plan dimensions). Wall panels in the JU-59, JU-60, and JU-61 systems were 14 cm thick, 1.2 m wide, and 2.6 m high (equal to the floor height) (Fig. 6). Floor panels were 12 cm thick, while their length and width were variable. The main difference between the JU-60 and JU-61 variants was in the material strengths (e.g. concrete grade was increased from MB-160 to MB-220), and improving panel connections.

Both floor and wall panels were reinforced with two layers of steel mesh. The size of horizontal and vertical reinforcing bars was rather small (ranging from 5-8 mm in diameter). Wall panels in the Jugomont system are considered as lightly reinforced according to the modern RC design standards, especially for buildings subjected to seismic actions.

Further evolution of the system led to new variants characterized by larger panel elements (JU-71). The original variants of the system were developed using smaller panel sizes due to limited construction equipment and low labour costs, however construction considerations changed over time - the new goal was to achieve faster building construction (faster assembly of panels at the construction site). As a result, wall panel length increased to 614 cm (compared to the previous 120 cm length), and the thickness was increased to 16 cm (compared to 14 cm thickness), while the height remained the same (258 cm - equal to the floor height). The thickness of floor panels remained unchanged (12 cm), while typical plan dimensions were 360 cm x 310 cm and 240 cm x 310 cm.

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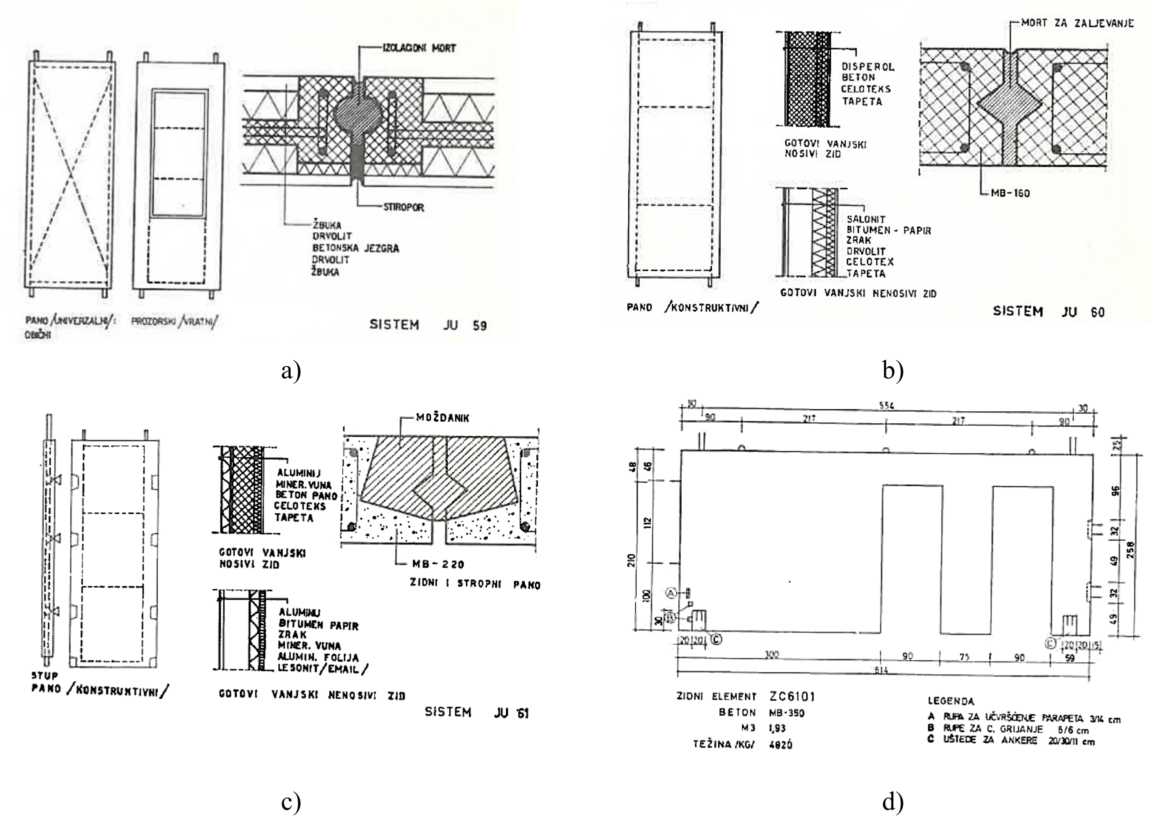

Figure 6. Variants of the Jugomont system – key structural elements: a) JU-59; b) JU-60; c) JU-61 and d) JU-71 [19]

Another variant of the Jugomont system, known as HG-68, was custom-developed for the construction of the "Potkovica" building in Blok 28, New Belgrade. The key structural components were based on the Jugomont system, however some improvements were introduced by the design team, which comprised of local engineers and a few engineering experts from the Soviet Union retained by the United Nations [22]. A typical wall panel in the HG-68 system was similar to the one characteristic for the JU-71 variant, except for more robust connections along horizontal and vertical joints (Fig. 7). For example, a larger number of extended vertical bars were provided along the horizontal joints, the configuration of shear keys along the vertical joints was changed, and extended horizontal bars were provided along the vertical joints [23].

Buildings constructed using the "Jugomont" system were known as "Limenke" (*cans* in English) due to the appearance of their façade elements, some of which were constructed using corrugated aluminium sheet cladding. Exterior walls were constructed either as structural or non-structural panels with 22 cm thickness. Structural exterior wall panels had 11 cm thick interior RC core, exterior thermal insulation and cladding (e.g. corrugated aluminium sheet), and interior finishing (e.g. wallpaper). Some of the façade panels were constructed with extended horizontal bars, which were intended for achieving connections between exterior and interior wall panels.

Wall panels at adjacent floors were connected by welding the vertical steel bars extended at the ends of the wall panels. Connections between the adjacent panels at the same floor were achieved through shear keys distributed along vertical joints. Voids between the panels were filled with cementitious grout (referred to as "mortar" in the technical literature related to this system) (Fig. 8a). Since no reinforcement was provided in the joints along the wall panel height, horizontal reinforcement in RC tie-beams at floor levels significantly contributed to the overall shear resistance of vertical joints (Fig. 9). It should be noted that the vertical connections were further improved in the JU-61 variant by inserting discrete RC (or steel) shear key elements between the adjacent wall or floor panels, see Fig. 8b [21, 25].

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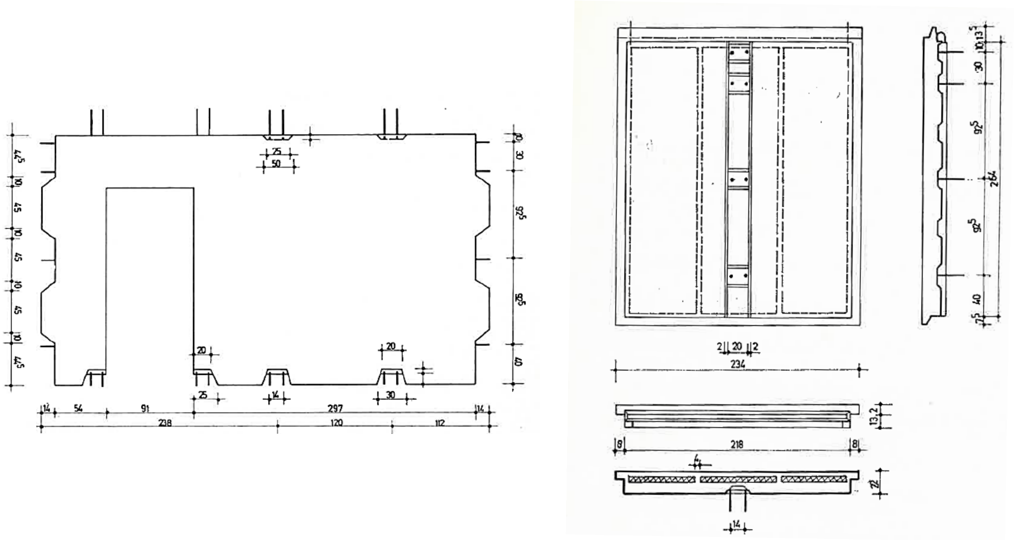

a) b)

Figure 7. Prefabricated wall panels, "Potkovica" building in New Belgrade (HG-68 variant): a) interior wall panel and b) exterior wall panel [23]

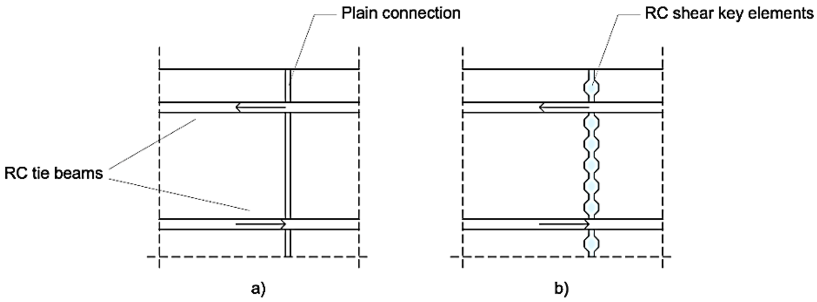

Figure 8. Vertical joints between adjacent wall panels: a) unreinforced shear keys and RC tie-beams at floor levels, JU-59 and JU-60 variants [24] and b) reinforced concrete shear keys, JU-61 and later variants [21]

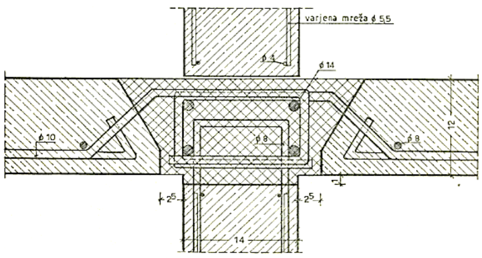

Figure 9. Horizontal joints – vertical section through a wall-to-floor panel joint, showing cast in-situ RC tie-beam, JU-61 [20]

4.3.Structural/seismic design philosophy

Reported case studies on the Jugomont applications for building construction in the 1960s and 1970s are invaluable for understanding the seismic design methodology for these buildings [20, 23]. Seismic design loads were determined according to the 1964 Yugoslav seismic design code [26], which was enforced at the time of original construction, but did not contain specific seismic design provisions for prefabricated concrete structures. Internal seismic forces in a building were determined according to the equivalent static analysis procedure. Distribution of shear forces to individual walls was performed in proportion to their relative stiffnesses, considering both flexural and shear effects [23]. The effect of spandrel beams was ignored (a cantilever model was used for the analysis).

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For the seismic design of the "Potkovica" building in New Belgrade, Serbia (constructed using a variant of the JU-61 system), seismic actions in longitudinal direction were solely resisted by the interior longitudinal walls, hence the contribution of exterior longitudinal walls in resisting seismic actions was ignored [23]. Since the exterior walls in that building had many openings and did not have spandrel beams, it was considered that they were rather flexible and would not be able to resist significant shear forces. Seismic shear forces in transverse direction were applied to all walls in proportion to their relative stiffnesses. It should be noted that earlier variants of the system (e.g. JU-59) did not have any longitudinal walls, which is considered a seismic deficiency since there is no lateral load resisting system for resisting seismic effects in that direction. Design of wall and floor panels was performed according to the Yugoslav design code for RC structures which was applicable at the time of construction and was based on the Allowable Stress Design approach.

Seismic design of panel connections is of particular interest since their integrity has a significant influence on the seismic behaviour and failure mechanisms for these buildings. The evidence related to the connection design and experimental proof testing is limited. It was reported that connections for the "Potkovica" building were designed according to the approach followed in the Soviet design practice, but the actual material properties were used in design calculations. It was also stated that the connections were tested experimentally and that the results confirmed a good agreement between the calculated design values and the experimental results [23].

4.4. Seismic behaviour and failure mechanisms of joints in wall panels

A lateral force-resisting system in an RC prefabricated panel building consists of vertical elements (walls), horizontal elements (diaphragms), and their connections. When these buildings are subjected to seismic loads, wall panels act as shear walls, and floor/roof slabs act as diaphragms. These diaphragms need to have sufficient strength and stiffness to permit rotation and deformation of the entire floor, hence connections between the slab panels need to be sufficiently strong. The diaphragms transfer lateral forces to wall panels through the connections at the interface between the diaphragms and wall panels.

Shear walls in these buildings need to resist seismic shear forces which are transferred from the diaphragms at each floor level, and transmit these forces and bending moments to the foundations. These shear walls are composed of prefabricated wall panels connected by means of horizontal joints at each floor level and vertical joints along the building height. Seismic behaviour and failure mechanisms for these buildings are significantly influenced by the integrity of panel connections. Seismic performance of prefabricated large panel buildings in the November 26, 2019 Durres, Albania earthquake is well documented [27].

A prefabricated RC shear wall is expected to perform like a cast-in-situ RC shear wall, provided that horizontal and vertical wall panel joints are sufficiently strong (Fig. 10a). However, when prefabricated RC shear walls have weak vertical joints between adjacent wall panels, a relative vertical slip may take place along the interface of adjacent wall panels, which may be subjected to rocking caused by overturning moments ("weak vertical joints") (Fig. 10b). Alternatively, when horizontal joints between the adjacent panels are weak, a horizontal (shear) slip may occur along the joints ("weak horizontal joints") (Fig. 10c).

Connections between adjacent wall panels in the Jugomont system are critical for transferring vertical shear forces along the joints (Fig. 11). As discussed earlier in this section, vertical panel joints were grooved along the panel height, and the voids were filled with grout/mortar (JU-59 and JU-60 variants) - this is similar to a plain surface connection (Fig. 8a). In subsequent variants of the system (e.g. JU-61), discrete shear keys were created along the vertical joints, and in some cases RC or steel elements were provided in these shear keys (Fig. 8b).

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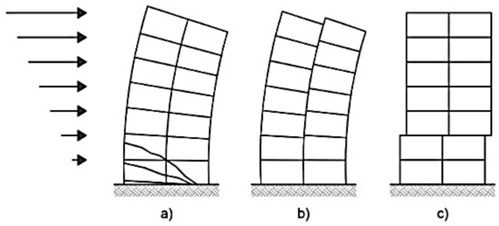

Figure 10. Seismic behaviour of RC structural walls composed of prefabricated wall panels: a) monolithic behaviour; b) weak vertical joints, and c) weak horizontal joints (based on [28])

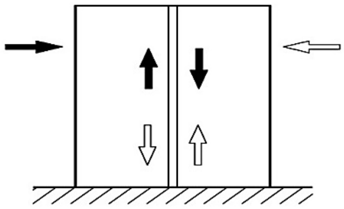

Figure 11. Lateral seismic forces and the corresponding internal vertical shear forces along a vertical joint between adjacent panels [29]

Structural behaviour of vertical connections in wall panels subjected to vertical shear forces depends on the connection type. A conceptual vertical shear force vs displacement (slip) relationship [29] shows differences in the capacity and displacements (slip) for a monolithic RC connection (cast in-situ wall), a plain connection of prefabricated panels (similar to the JU-59 and JU-60 variants), and a shear key connection (similar to JU-61 system) (Fig. 12). It is clear that a monolithic connection is characterized by the largest capacity and smallest displacements, while plain and shear key connections are expected to experience significantly larger displacements. It is also expected that the capacity of a shear key connection is going to be significantly larger than a plain connection.

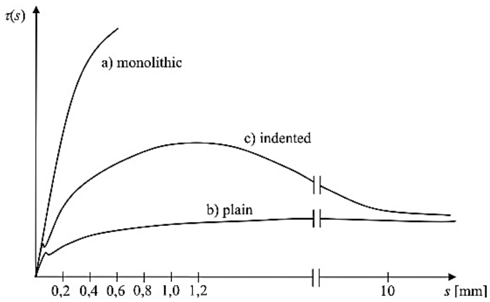

Figure 12. Vertical shear force versus displacement (slip) relationship for different RC panel connections [29]

Structural behaviour of RC wall panel connections with shear keys subjected to monotonic shear loading has been studied for more than 50 years. An early study on the structural behaviour and shear capacity of a shear key connection was performed by Cholewicki [30], who considered a shear key connection along the panel height and horizontal (longitudinal) reinforcement in RC tie-beams at floor levels. There are two distinct phases of progressive failure of the connection (Phase I and Phase II) (Figure 13). Initially, a shear key connection is very stiff, and adhesion between the panel surface and grout effectively transfers shear stresses between the panels (Phase I). With an increase in the applied shear force, cracking takes place at the interface between the panel and the grout, resulting in relative slippage (this is referred to as splitting). Once the slippage commences along the vertical cracks (Phase IIa), the shear is transferred by means of shear friction through horizontal reinforcement in RC tie beams. Finally, diagonal cracks occur across the shear keys and are aligned in the direction of principal stresses within a shear key (Phase IIb). At that stage, the connection is expected to attain the ultimate resistance.

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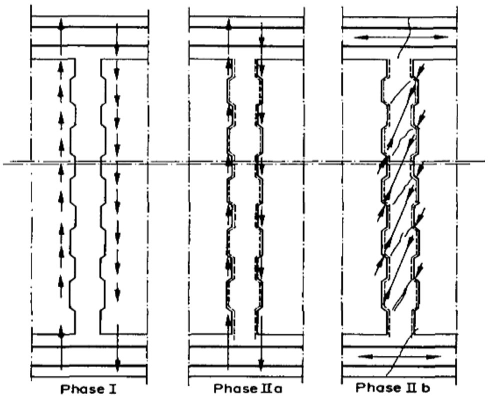

Figure 13. Progressive failure of a shear key connection between adjacent prefabricated RC wall panels [30]

Experimental studies on RC panel specimens with different configurations of shear key connections and a plain surface connection were performed by Rizkalla et al. [31] and Foerster, Rizkalla, and Heuvel [32]. Based on the experimental results, the authors proposed a shear force versus displacement (slip) relationship for a shear key connection (Fig. 14). The authors also proposed equations for estimating the capacities of the connection at critical stages (cracking, maximum, and ultimate).

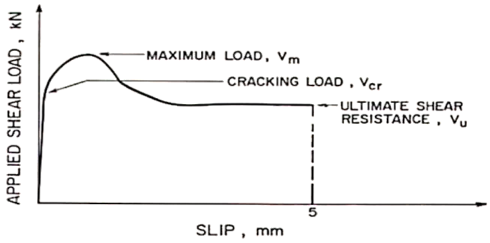

Figure 14. Vertical shear force versus displacement relationship for a shear key connection in a wall panel [31]

The experimental results showed a significant effect of the type of connection on the capacity of panel connections based on the testing of 7 large-scale specimens [31] (Fig. 14). A shear key arrangement (large versus small shear keys) did not have a significant effect on the connection performance: specimen 1LK2 (with large shear keys) demonstrated a similar performance like specimen 2SK2 (with small shear keys). The effect of compression stress perpendicular to the connection was significant: specimen 1LK2 (subjected to 2 MPa compression) attained a significantly lower maximum capacity than specimen 2LK4 (subjected to 4 MPa compression).

Horizontal connections between wall panels are critical for maintaining their integrity under lateral seismic loads. The following three types of failure mechanisms are possible for RC panels subjected to combined effects of lateral seismic forces and gravity loads (Fig. 15): a) shear sliding failure along a horizontal panel joint, b) flexural tensile failure, characterized by tensile deformations, and possibly a failure of vertical reinforcement within tensile zone of the connection, and c) flexural compression failure, characterized by high compression stresses and crushing of concrete within the compressed wall end zone.

These failure mechanisms may be possible in the context of buildings constructed using the Jugomont system. A sliding failure mechanism along horizontal panel joints may develop when shear friction resistance, contributed by vertical reinforcing bars and frictional resistance along the mortar interface, is not adequate to resist the applied seismic loads. Shear friction resistance along interfaces in RC structures is well established, and can be estimated according to design codes for RC structures, e.g. Eurocode 2 [33].

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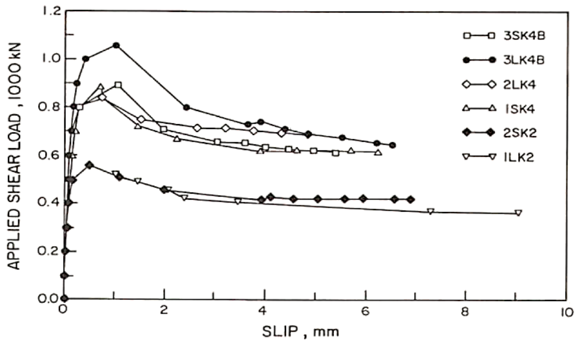

Figure 14. Experimental results for vertical shear force versus slip response for six wall panel connections with different shear key arrangements [31]

A flexural tension failure of the wall panels in the Jugomont system is governed by tensile resistance provided by extended vertical reinforcing bars, which were welded at the construction site (at the assembly stage). Given the small size and number of extended bars at wall panel ends, it is expected that their tensile capacity is relatively small. On the other hand, quality of field welding may be deficient in some cases (and is difficult to determine after the construction has been completed). When a prefabricated RC shear wall is subjected to significant overturning moments induced by seismic actions, either a reinforcing bar fracture or weld failure may take place.

Finally, a flexural compression failure could take place in prefabricated RC shear walls due to large seismic overturning moments, which may induce crushing of compressed concrete at the wall base (toe). This mechanism may be possible in prefabricated RC shear walls in buildings constructed using the Jugomont system, especially given a relatively small concrete compressive strength and a small wall thickness (14 -16 cm).

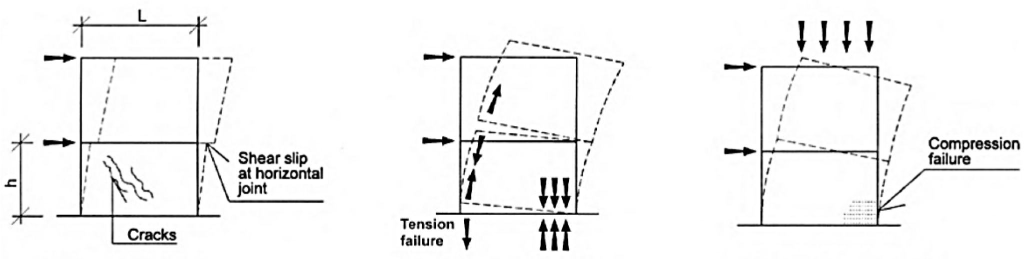

Figure 15. Failure mechanisms for horizontal panel connections: a) shear slip along a horizontal joint; b) flexural tension failure, and c) flexural compression failure (based on [24]).

5. Conclusions

Prefabricated RC buildings constitute a significant fraction of the existing building stock in urban areas of Eastern European and Central Asian countries. Majority of these buildings were constructed using prefabricated RC panel systems during the post-WWII period. Jugomont system was one of the most popular prefabricated RC panel systems in former Yugoslavia, hence there are many existing buildings constructed using that system in the region.

Some of the buildings constructed using "Jugomont" system are located in areas characterized by moderate to high seismic hazard, especially in urban areas of Croatia and Slovenia. In order to assess seismic risk associated with these buildings it is necessary to understand the original architectural and structural/seismic design concepts. Possible failure mechanisms of these structures due to seismic actions are generally well established. It is possible to quantify characteristic force versus displacement response for panels and their connections, and the corresponding acceptance criteria needed for seismic assessment of these buildings. Challenges associated with numerical modelling of these structures are associated with input parameters such as mechanical characteristics of panel materials and their connections. Particular challenge is associated with the behaviour of connections under seismic actions, given that available experimental studies related to structural response of panel connections subjected to monotonic and especially reversed cyclic loading are extremely scarce. Comprehensive analytical studies, considering numerical models or prefabricated RC walls with variable mechanical properties of construction materials and connection types, are needed in the context of seismic risk assessment for urban building portfolios.

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