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SEISMIC BEHAVIOUR OF PREFABRICATED WALL PANELS: AN OVERVIEW

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Abstract

Recent global events such as earthquakes, the COVID-19 pandemic, wars, floods, and similar crises, which have also affected Croatia, have highlighted the urgent need for rapidly deployable emergency shelters, hospitals, and both temporary and permanent housing solutions. Simultaneously, cities worldwide are grappling with accelerated population growth, creating a huge need for residential areas.

Prefabricated construction is an efficient solution to these challenges. It enables the faster construction of a greater number of industrial and residential units, helping to reduce demand while lowering the cost per square meter of housing or commercial space. In addition, prefabricated construction is considered sustainable as it minimizes the amount of waste and optimizes the use of materials [1]- a key advantage in today's construction industry.

Prefabricated wall panels, a fundamental component of such structures, are increasingly being used worldwide. However, these panels must meet stringent mechanical resistance and stability requirements to withstand all foreseeable impacts. It could be said that prefabricated wall panel systems are particularly susceptible to seismic (dynamic) actions. Numerous scientific studies have addressed this issue and undoubtedly established that the seismic resistance of these systems, and therefore of the entire prefabricated construction, is largely dependent on the quality of the joints between the panels.

The increasing number of prefabricated buildings, coupled with the growing frequency of earthquakes worldwide, has amplified the need for in-depth research on the seismic resistance of prefabricated reinforced concrete structures, where the greatest emphasis is placed precisely on prefabricated wall panels, i.e. on their mutual connections. For this reason, this paper aims to compile and analyze the conclusions and observations of previous research conducted by scientists worldwide on the topic of prefabricated reinforced concrete wall panels and their connections under the influence of earthquakes.

Keywords: seismic behaviour, prefabricated wall panels, prefabrication, connections, earthquake, etc.

1. Introduction

Conventional monolithic construction implies on-site building, which demands extensive space, labor, and machinery. Additionally, it is limited by weather conditions and other site-specific factors. This method reduces the potential for reusing and recycling materials, resulting in higher energy and time consumption and, consequently, increased CO_2 emissions. Higher CO_2 emissions contribute to climate change and atmospheric warming, leading to extreme weather events such as floods and droughts. This is a pressing global issue, underscored by the commitment made in the Kyoto Protocol, where EU member states and several other countries committed to cutting greenhouse gas emissions by 20% by 2020. The EU has since raised its target, committing to a 55% reduction by 2030 [1]. On the other hand, prefabricated construction is faster, more sustainable, and uses less time and energy, as components are

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manufactured in factories, delivered to the site, and assembled on the location. This approach minimizes the dependency on weather and site conditions while allowing for greater quality control in production. Prefabricated elements can be easily reused, disassembled, and reassembled at different locations, making recycling much more feasible. Consequently, this reduces waste, and the energy required for production and recycling, ultimately lowering pollution levels. In addition, prefabricated components can be constructed with advanced insulating materials that improve their energy efficiency and the overall performance of the building, particularly in terms of thermal and acoustic insulation. Precast walls can also be designed with pre-installed ducts for utilities which significantly speeds up the installation of electrical, plumbing, and other systems. This reduces the need for additional construction work, saving both time and effort during the building process. Controlled factory environments make it easier to maintain consistent quality, and the use of advanced machinery, resulting in highly consistent outcomes and fewer structural issues. This is in contrast to traditional monolithic construction, where quality can vary significantly due to unstable weather conditions, human error, and various complications on site. Achieving consistent quality across all areas of a project is more challenging in conventional construction, as environmental and logistical factors are harder to manage.

Furthermore, rapid population growth demands quick solutions to meet housing needs. There is an increasing demand for residential units in the shortest possible time, and prefabricated construction provides a practical solution to this challenge. Unfortunately, the use of prefabricated construction is limited due to the lower load-bearing capacity of prefabricated structures under dynamic loads. For example, the 2012 Emilia earthquake led to the collapse of structures that were not properly connected. There have been several other instances where such structures sustained damage, primarily due to an insufficient understanding of the behaviour of joints and structural systems under stress [2]. Table 1 summarizes the key differences between prefabricated and monolithic construction based on specific criteria.

Although prefabricated construction offers numerous advantages, one notable drawback lies in the limited understanding of the behaviour of such structures, particularly under dynamic loads, such as earthquakes. Consequently, research into the behaviour of prefabricated structures has increased recently, with significant progress made over the past decade. In 1989, Foerster et al. [3] studied the behaviour of shear connections in prefabricated wall panels. Similar research continued through the 1990s, further exploring and refining the performance of these connections [4], [5], [6], [7]. In 2011, Pavese and Bournas [8] conducted an experimental study on the behaviour of prefabricated sandwich wall panels, both with and without openings, varying the dimensions of the openings, under seismic loading. They simulated the behaviour of fixed-end walls and cantilever walls. The tests revealed a strong interaction between shear and flexure due to the squat geometry of the panels. In their 2016 study, Palermo and Trombetti [9] proposed a new structural system that is consisted of lightly reinforced concrete sandwich panels characterized by a small proportion of reinforcement and a thin concrete layers. The system was tested under cyclic loading, and a non-linear model was developed, showing a strong correlation between experimental results and model predictions. It was concluded that the seismic performance of this structural system, in terms of ductility, strength, and stiffness, is comparable to that of monolithic RC (reinforced concrete) walls. However, greater attention needs to be given to the connections between such panels and the foundations. Research in this field continues, with Xu et al. in 2017 [10] investigating the seismic behaviour of wall panels with sleeve connections. Their study compared the performance of these panels to that of cast-in-place specimens and proposed several types of wall panel connections. Vaghei et al. [11] introduced an innovative method for connecting vicinal wall panels using two U-shaped channels joined through a male-female mechanism, secured with bolts and nuts. To enhance performance, a rubber element was integrated into the connection to effectively dissipate vibrations. Guo et al. [12] developed a new dry connection using high-strength bolts and plates, which was tested under shear loading and tension.

As prefabricated construction gained popularity, the number of published studies on this topic also increased, along with the variety of proposed and investigated types of wall panels, their

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interconnections, and their connections to foundations and floor systems. According to the graph presented by Martins et al. [1] in Figure 2, the number of publications related to prefabricated wall panels (or their connections) rose after 2019, indicating a growing interest in prefabricated construction overall. This surge can likely be attributed to the COVID-19 pandemic, which created a pressing need for rapid construction of hospitals capable of accommodating large numbers of patients. A prime example of the capabilities of prefabricated construction is the Huoshenshan Hospital in China, built in just 10 days using prefabrication.

As mentioned earlier, 2019 saw an increase in interest in prefabricated construction, alongside a growing focus on sustainable building practices and climate change. Sebaibi et al. [13] focused on exploring methods to enhance energy efficiency in the prefabricated construction industry by minimizing the environmental impact of concrete through the incorporation of ground granulated blast furnace slag (GGBS) and ultrafine Portland cement (UC) and by removing thermal treatment. Conversely, a growing emphasis on innovative solutions is evident, both in the development of connection systems and the design of prefabricated wall types. Zhou et al. [14] introduced a novel dry connection method, referred to as sleeve and box connections, demonstrating its potential in prefabricated construction. Similarly, Han et al. [15] conducted a detailed investigation into the behaviour of double composite walls, with a particular focus on the influence of bolts within shear-loaded wall connections, providing valuable insights into their structural performance.

The analyzed data provide valuable insights into the benefits of prefabricated construction. However, there is still room for improvement and the development of advanced prefabricated wall panels and connection systems with enhanced seismic performance. These opportunities for progress extend beyond structural optimization, encompassing economic efficiency and sustainability considerations, thereby highlighting the necessity for further innovation in the field of prefabricated construction. The main purpose of this research is to provide a comprehensive review of the existing literature on this topic. The aim is to offer insights into innovations related to types of wall panels and their connections, as well as to provide an overview of the seismic testing methods that have been conducted so far. Additionally, the paper seeks to trace the progress of research over time and summarize the key findings of researchers worldwide. It also aims to highlight the existing gaps in the field, identify areas that require further investigation, suggest potential improvements, and provide recommendations for future research directions.

Table 1. Summary table

Criteria	Prefabrication	Monolithic construction
Construction time	Faster, simultaneous with site preparation	Slower, sequential
Quality control	High, standardized in factories	Variable, dependent on site conditions
Waste	Minimal, factory reuse possible	Higher due to reuse on-site
Energy consumption	Lower due to efficient production	Higher due to extended on-site work
Environmental impact	Minimal on-site, lower pollution	Higher site disruption, noise, and dust
Design flexibility	Moderate, modular focused	High, adaptable to custom designs
Cost	Potentially lower, with less labor	Often higher, with more labor required
Safety	Safer, controlled environment	More hazardous, dynamic on-site risks
Sustainability	Higher, easier to recycle	Lower, difficult to deconstruct

2. Types of precast walls

Progress in the study of wall panels and their response to seismic loads have driven the development of innovative ideas and increasingly effective design solutions. This progression has led to the emergence of various panel types, distinguished by differences in core materials and cross-sectional configurations. According to the literature, wall panels can be systematically categorized based on their assembly techniques and cross-sectional characteristics. These classifications primarily include three types:

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sandwich wall panels, plain wall panels, and double wall panels. The following presents recent research by scientists regarding the previously mentioned types of walls.

2.1.Sandwich wall panels

In a study conducted in 2011 [8], the seismic performance of prefabricated sandwich wall panels was investigated through experimental testing. The panels were composed of two layers of sprayed concrete reinforced with wire mesh and a core of Expanded Polystyrene foam. Experimental tests were performed on specimens with and without openings, simulating the structural behaviour of cantilever and fixed-end walls. The results indicated that the proposed panel system shows potential for use in regions characterized by moderate and, potentially, high seismic activity. In his recent study, Hou, Hetao [16] proposed a novel type of wall sandwich panel consisting of an EPS (expanded polystyrene) core serving as insulation, flanked by two external panels reinforced with wire mesh. The external panels are interconnected by diagonal steel bars welded to the wire mesh reinforcement. The reinforced panels' inner surface can be either ribbed or flat. The study concluded that the diagonal bars are sufficient to transfer shear forces between the external panels, enabling the system to achieve full composite action for bending moment resistance. Additionally, it was noted that while the ribbed surface of the reinforced panels reduces the overall mass of the system, it may, on the other hand, lead to decreased flexural resistance in the sandwich wall panel. Figure 1. shows these types of sandwich wall panels. Ricci et al. [17] experimentally investigated the seismic performance of a novel type of sandwich squat wall panel. The structural system comprises a central layer of expanded polystyrene with a thickness ranging from 60 to 160 mm, enclosed by two outer layers of sprayed reinforced concrete. Seismic tests were conducted on the walls and their connections, leading to the conclusion that these panels exhibit behaviour closely resembling that of reinforced concrete wall panels. It is also important to highlight that this system is particularly well suited for low-rise residential buildings, where walls are longer than they are wide.

Figure 1. A novel type of sandwich wall panel investigated by Hou, Hetao [16]

2.2.Plain wall panels

Todut's 2014 study [18] presents findings from an experimental program examining the seismic performance of precast reinforced concrete wall panels with and without openings. All tested panels exhibited shear-type failure, significantly influenced by the type and size of openings, with critical areas and insufficient reinforcement observed in specific regions. Experimental observations revealed extensive cracking across all panel regions, reinforcement yielding, concrete crushing, and diagonal cracks in the piers. Panels with large openings showed notable reductions in stiffness and lateral resistance, along with reduced energy dissipation compared to panels with smaller openings. However, panels with larger openings demonstrated a greater deformation capacity. Overall, panels with small

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openings were more effective in dissipating seismic energy, while large-opening panels exhibited increased deformability at the cost of reduced structural stiffness and energy dissipation. Figure 2. shows the manufacturing process of prefabricated reinforced concrete wall panels.

Figure 2. Manufacturing process for plain wall panel [18]

Bruno Dal Lago [19] explored the structural performance of a novel lightweight precast concrete wall system, developing two distinct solutions. The first solution involves a fully lightened wall, where selected hollow cavities are filled with in-situ concrete after the placement of reinforcing steel cages. The second solution features a partially lightened wall, where solid sections are cast during production, and the connections are formed using pre-installed mechanical devices, like rebar couplers. In his 2017 study, Guoshan Xu [10] investigated the seismic performance of a precast RC shear wall with a single-row grout-filled sleeve connection, designed for six-story precast box-modular structures with RC shear walls. The paper introduces a force-displacement mixed control method to manage the seismic response. Experimental results demonstrated that this method effectively controlled rotations, lateral deformations, and axial forces in specimens subjected to quasi-static cyclic loading. Additionally, a comparison between the prefabricated sandwich wall panels and a cast-in-situ specimen showed similar behaviour in terms of inter-story drift angle, failure mode, stiffness degradation, ultimate force, energy dissipation capacity, and ductility under combined axial-flexural-shear loading.

2.3.Double wall panels

Mackechnie, James R. in his 2013 study [20], explored the thermal performance of a 250 mm thick double wall composed of multiple layers shown in Figure 3. Toward the exterior, a 125 mm lightweight layer was placed, serving as thermal insulation, followed by a transition layer, and finally, a 75 mm thick heavyweight layer. The heavyweight layer was reinforced and provided thermal mass. The research progressed with the work of Han S. [15], who investigated the behaviour of double walls composed of two reinforced wall panels with ribbed cross-sections, connected using bolts. The space between the panels was then filled with cast-in-place (CIP) concrete. The specimens varied in design, including differences in the filling material, which was tested in reinforced and non-reinforced configurations. In a further advancement, Kim, Seungho [21] proposed an innovative double precast wall panel type consisting of two thin panels interconnected by lattice bars. The study aimed to improve the efficiency of retaining wall construction and to address existing challenges in reinforced concrete systems, offering a more effective solution for modern construction applications.

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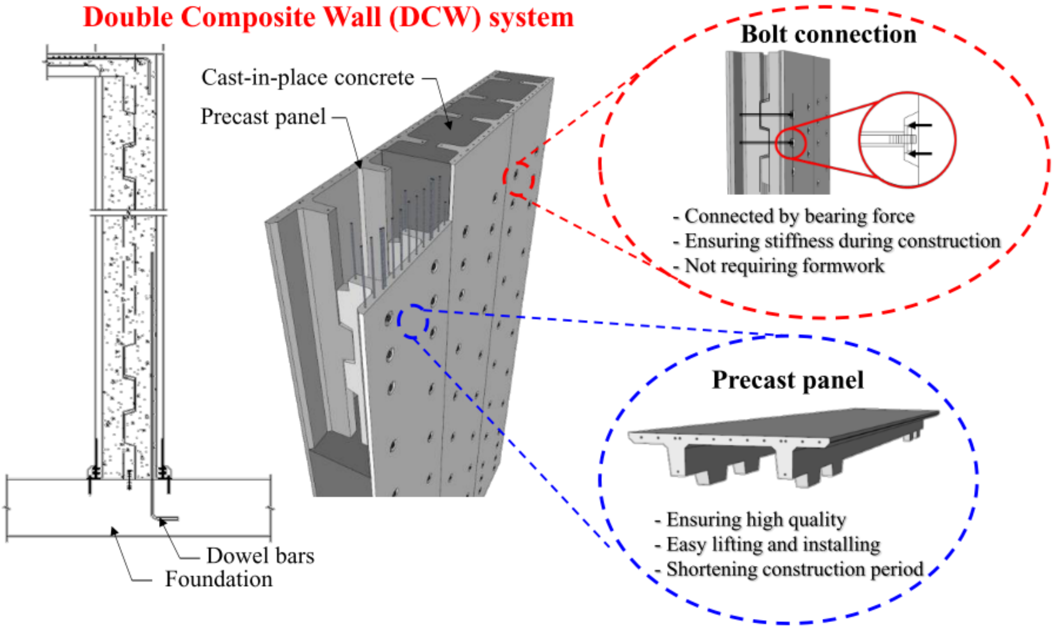

Figure 3. DCW system explored by Mackechnie, James R [20]

3. Precast wall connections

Load-bearing walls, including precast reinforced concrete walls, are required to effectively transmit vertical and horizontal loads without exceeding the ultimate or serviceability limit states. The connections between precast wall panels represent critical components in structural systems, as they must accommodate stresses induced by structural displacements caused by external loading or inherent concrete deformations, such as shrinkage, swelling, and thermal effects. Moreover, these connections play a key role in maintaining the overall stability of structural systems under seismic loading. It is well established that the seismic performance of precast wall systems is significantly affected by the design and implementation of panel connections.

To achieve satisfactory load-bearing capacity of the structural system, particularly under seismic actions, wall panels must be properly connected to the foundations, floor systems, and adjacent panels through both vertical and horizontal joints. These joints can be classified based on the type of structural elements they link or the technology employed in their construction. Depending on the construction methodology and materials utilized, joints are broadly categorized into wet and dry connections. Table 2. presents a chronological summary of scientific research and proposed joint typologies, predominantly assessed under shear stress conditions. These investigations aim to develop joint configurations that exhibit superior performance when subjected to seismic loads.

Table 2. Literature review on types of connections

Type of connection	**Authors**	**Year**	**Proposed/investigated types of connections**
Wet connections	Soudki, Khaled A et al. [6]	1996	(a) The dry pack plain surface connection features a flat surface area filled with dry pack; (b) Multiple shear keys - The shear keys and the space between the panels are entirely filled with dry pack grout. There is no vertical reinforcement included at the connection interface to examine the effect of the shear keys only; (c) Rebars welded to the steel angle- The connection comprises a flat surface area featuring two mild steel bars. The straight bars extending from the top panel are welded to a steel angle located in an open pocket in the lower panel. After the welding process, the space between the panels is embedded with dry pack grout.

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	Xu, Guoshan et al. [10]	2017	(a) a horizontal connection between walls where longitudinal reinforcement is indirectly spliced using grout-filled sleeves arranged in a single row; (b) a vertical connection between walls, featuring a stirrup that is bolted to vertical reinforcement; and (c) a non-composite floor slab joint
	Li, Jianbao et al. [22]	2017	Vertical seam connection that is divided into two groups (I and II) based on the placement of the columns' longitudinal reinforcement. Group I specimens, the longitudinal reinforcement is partially embedded in the prefabricated section, with the rest placed in the cast-in-place section. In contrast, all longitudinal reinforcement in Group II specimens is arranged entirely within the cast-in-place section.
	Biswal, Aparup et al. [23]	2019	Plane joint with U-bars at 250 mm spacing, plane joint with loop boxes at 250 mm spacing, plane joints with U-bars at 125 mm spacing, castellated joint with U-bars at 300 mm spacing, castellated joint with loop boxes at 300 mm spacing, and castellated joint with edge lips and loop boxes at 300 mm spacing
	Seifi, Pouya et al. [24]	2019	Connections with grouted metal ducts where bars are extending from the foundation, embedded within metal ducts later filled with non-shrinkage grout, while another end of the reinforcement was anchored into the foundation with a standard 90-degree hook. Variations were made in the shape and amount of reinforcement within the connection, as well as in the wall thickness.
	Kothandapani, Karthikeyan et al. [25]	2019	In the first set of specimens, rebars were used as dowels, with varying diameters, quantities, and spacing, as well as their position. Diameters of 10 mm and 12 mm were used at a spacing of 300 mm, 250 mm, and 150 mm. In the second set of specimens, gusset plates, steel angles, and bolts were used at the joint to connect the top and the bottom section either vertically, diagonally, or combined.
Dry connections	Foerster, Harry R et al. [3]	1989	(a) 20 mm wide dry pack grouted connection, (b) 25M continuity bars with dry pack grout, (c) 25M continuity bars with dry pack grout and type A shear connectors, (d) 25M continuity bars with dry pack grout and type B shear connectors, (e) dry pack grouted shear keys.
	Rizkalla, Sami H et al. [26]	1989	Three types of connections were tested: (a) a plain surface connection, 20 mm thick, and two types of shear key connections: (b) Small key consisting of four 50 mm high and 70 mm wide slots and (c) Large key consisting of two slots 100 mm high and 90 mm wide. The space in between was filled with a dry pack composed of sand, Portland cement, and water in a ratio of 2:1:0.2.
	Soudki, Khaled A et al. [6]	1996	(a) Dry pack Plain Surface specimen had a plain surface region that was filled with dry pack. This specimen was used as a controlled specimen to determine the impact of the dry pack on the connection behaviour. (b) Multiple dry packed shear keys without any reinforcement to focus on the shear keys' influence only. (c) A specimen with two mild rebars welded to a steel angle in the lower panel projecting into the upper panel. Following the welding, the gap between the panels is filled with a dry pack grout. (d) Post-tensioned strand connection is provided using two seven-wire strands positioned within galvanized steel ducts embedded in the panels. After the post-tensioning process, the ducts were infused with expansive grout. (e) Post-tensioned bars type of connection was the same as the previous one with the difference in the diameter and grade of the bars. Here, two 15.8 mm diameter prestressing bars with 1080 grade were used.
	Crisafulli, F. J. et al. [27]	2003	A welded steel consisting of a rectangular steel plate with a centrally located circular hole, measuring five hole diameters in length and 1.6 hole diameters in high welded with a weld thickness of *t*.
	Brunesi, E. et al. [28]	2017	The connection is achieved by leaving a hole of specified dimensions, which is subsequently grouted with mortar. Inside the hole, there is a hook connected to the longitudinal reinforcement using bolts and a steel plate.
	Wang, Wei et al. [29]	2018	The connection is established by welding the longitudinal reinforcement of the lower and upper panels to the connecting steel plates. A layer of high-strength mortar is cast on top of the lower panel beforehand. The steel plates

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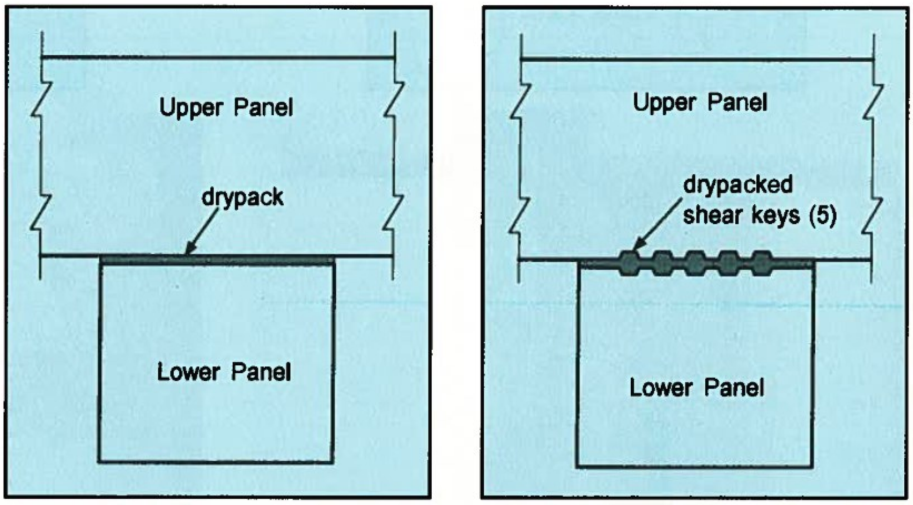
		from the lower panel are inserted into pre-formed channels in the upper panel. The positions of the upper and lower plates are adjusted to align the pre-defined holes on the plates, through which a bolt is inserted and tightened, securing the connection.
Psycharis, Loannis N. et al. [30]	2018	(a) Rebar connections are achieved using reinforcement bars that protrude from the panels and fit into prepared ducts within the beams while the space between the reinforcement bars and ducts is filled with non-shrinking, high-strength grout or epoxy resin. (b) Wall shoe connections are constructed using an anchor bolt set into the beam and a steel "wall shoe" built into the panel. (c) Steel plate connections use steel nests embedded in both the beam and the panel, which are secured to one another via a connecting plate.
Vaghei, Ramin et al. [11]	2019	Connection is achieved by utilizing two steel U-shaped channels attached to the sides of the walls. These channels are fastened together as male and female joints using bolts and nuts to ensure a secure connection. Additionally, a U-shaped rubber element is placed between the two channels to help dissipate vibrations within the structure.
Cai, Gaochuang et al. [31]	2019	Demountable vertical bolted joints were created using three reinforced concrete blocks, detachable steel bolts, and steel plates. The steel bolts and plates were arranged and the concrete blocks were joined together with secured bolts to form specimens.
Sun, Jian et al. [32]	2019	The horizontal connection between two wall panels is achieved using an H-connector and high-strength bolts. First, the top and bottom steel units, which have pre-drilled holes for the bolts, are cast onto the wall panels. Then, the H-connector and high-strength bolts are used to complete the connection.
Guo, Wei et al. [12]	2019	A new dry connection proposed here consists of high-strength bolts and anchored steel plate. The steel plate is made of Q345 steel, and is anchored using welded HRB400 rebars. To secure the walls, 10.9-grade high-strength bolts are used.
Zhou, Yun et al. [14]	2021	The sleeve connector and box connector are embedded within concrete wall panels or footing slabs. At the connection point, a 16 mm diameter screw bolt extending from the sleeve connector is inserted into a corresponding 16 mm hole in the box connector, securing the connection between the sleeve and box connectors. Finally, the gap between the connectors is filled with high-strength grout.



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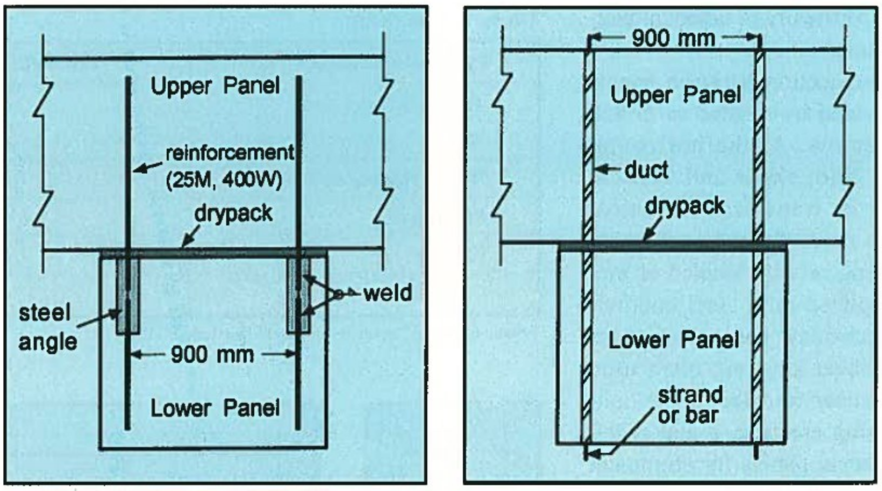

Figure 4. Respectively: dry pack grout-only connection; shear keys connection; reinforcing bars with welded connection; post-tensioned connection using strands or bars [6]

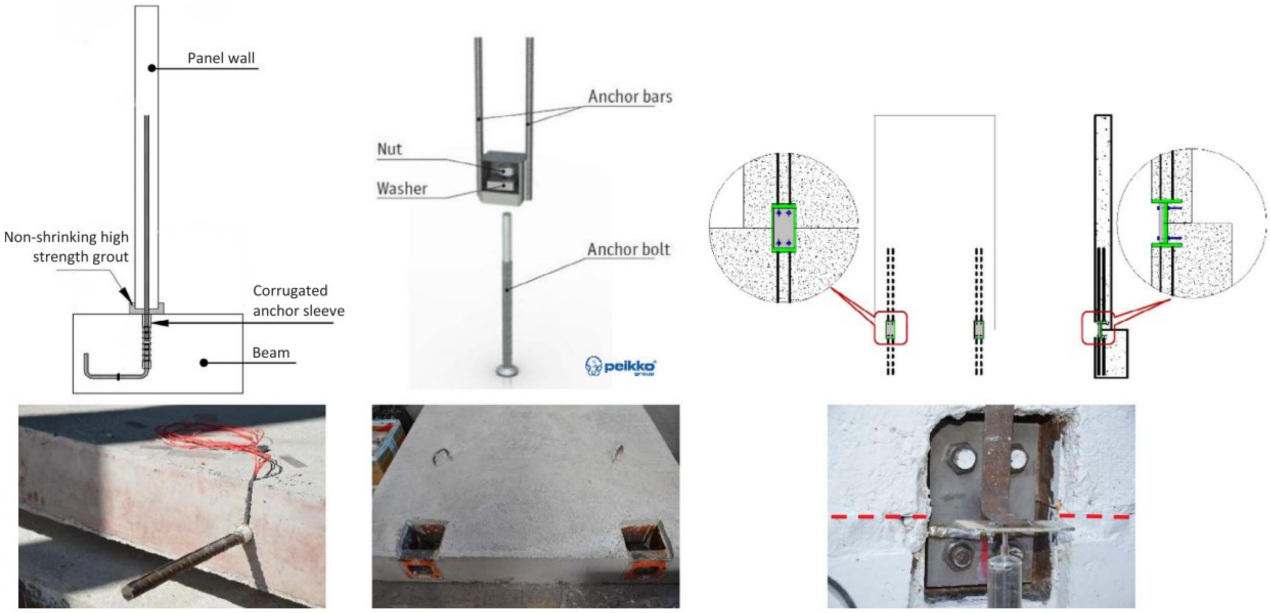

Figure 5. Types of connections considered in the research by Psycharis, Ioannis N. (2018) [30] respectively: "'Rebar' connections','Wall shoe' connections and 'Steel plate' connections"

4. Conclusion

The review of scientific studies, presented in this paper, offers a comprehensive analysis of prefabricated wall panels and their seismic performance, focusing on panel types and connection methods. The investigation encompassed three main types of wall panels - double panels, sandwich panels, and plain panels - highlighting their structural behaviour under earthquake-induced loads. Experimental studies reviewed in the literature emphasize the advantages and limitations of each panel type, particularly in terms of strength, stiffness, energy dissipation and deformation. Double panels, while providing simple solutions, may exhibit increased material usage, whereas sandwich panels show superior thermal performance and moderate seismic resistance. Plain panels, being simpler in design, may be less effective under significant seismic loads but offer cost efficiency.

Additionally, two principal connection systems, wet and dry joints, were evaluated, with detailed descriptions of variations tested in the reviewed works. Wet joints, often involving concrete infill or

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grouted connections, demonstrated enhanced stiffness and continuity but could be labor-intensive and sensitive to construction quality. Dry joints, typically utilizing mechanical fasteners or interlocking elements, provided greater flexibility and ease of assembly but there can be a challenge in achieving optimal energy dissipation. The findings collectively underscore the critical influence of panel and joint selection on the seismic resilience of prefabricated structures.

In conclusion, the reviewed studies suggest that an optimized combination of panel type and joint configuration is essential to balance structural performance, construction efficiency, and cost. Future research should focus on optimizing these systems to enhance seismic resistance, sustainability, cost efficiency, and adaptability to diverse construction demands. The findings contribute important insights to the field of prefabricated construction, supporting informed decision-making in the design and implementation of modern building systems.

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