Canadian Conference - Pacific Conference on Earthquake Engineering 2023
Vancouver, British Columbia
June 25th – June 30th, 2023

Review of Seismic Design Provisions of Precast Concrete Shear Walls

Chadia Uwamahoro[1*] and Lisa Tobber[2]

[1]PhD Student, School of Engineering, University of British Columbia, Kelowna, BC, Canada
[2]Assistant Professor, School of Engineering, University of British Columbia, Kelowna, BC, Canada
[*]chadia93@student.ubc.ca (Corresponding Author)

ABSTRACT

Precast concrete systems are widely utilized due to their exceptional quality and efficient construction process. In precast concrete construction, structural elements, such as shear walls, are fabricated in a certified controlled plant, ensuring the components' quality and durability. These elements are then transported to the construction site and assembled in position to form a complete structure. This modular construction process results in a seismic response of precast concrete structures fundamentally different from cast-in-place (CIP) concrete shear walls, even when the connection design aims to emulate them. This paper examines the seismic design provisions and construction methods for precast concrete shear walls in Canada, the United States, and New Zealand, highlighting the differences and similarities among these regions. It also identifies the gaps in current design provisions for precast concrete shear walls and suggests steps to address these shortcomings. By comprehensively understanding the current seismic design of precast shear walls and exploring ways to improve it, the total precast concrete system can potentially address some of Canada's pressing housing and commercial building needs.

Keywords: Precast concrete, shear wall, seismic design, provisions

BACKGROUND AND INTRODUCTION

Precast concrete construction is an effective method for constructing multi-story buildings. Its many advantages over traditional CIP, such as construction speed, all-weather construction, less material usage, and enhanced site safety, make it increasingly popular, including in areas of high seismicity. Figure 1 shows examples of precast construction.

(a) *(b)* *(c)*

Figure 1. Precast building: (a) The Paramount (San Francisco, 2002), (b) 203 Albert, Waterloo, Canada c) Southern Cross Medical Building exterior, Christchurch, New Zealand

As the popularity of precast concrete increases, the seismic response of such systems, particularly systems with low-ductility, remains insufficiently understood. Furthermore, there is limited seismic design guidance on these systems globally. This paper investigates seismic design provisions for precast concrete shear walls, Canada's most common seismic force-resisting system for precast concrete buildings. It then compares the Canadian design philosophies to those used in the United States and New Zealand. It also identifies gaps and challenges in current design provisions for precast concrete shear walls and proposes steps for future research.

SHEAR WALLS AND CONNECTIONS

Shear walls, shown in Figure 2, are commonly used to resist the lateral load in precast concrete buildings. They can be installed as interior walls, exterior wall systems, or walls of the elevator, stairways, mechanical shafts, or cores. According to the Canadian Precast/Prestressed Concrete Institute (CPCI), shear walls serve as cantilever beams transferring the lateral forces generated by the superstructure to the foundation [1]. The number of shear walls required for a structure depends on several factors, such as the wall's bending and shear resistance and the foundations' characteristics.

Figure 2. Precast wall panels as shear walls [2].

Shear wall panels are connected using two types of joints: vertical and horizontal. Vertical joint connections are primely used to transfer lateral forces to the adjacent panels. Horizontal joints, located at the junctions of the foundations or wall-to-wall interface on each floor, serve various functions, such as supporting gravity load, transferring horizontal shear, and resisting tension/compression forces caused by lateral loads. Typically, the vertical reinforcement is spliced at the horizontal joint. It resists in-plane shear and provides shear friction reinforcement across the joint [1]. Figure 3 shows the types of connections.

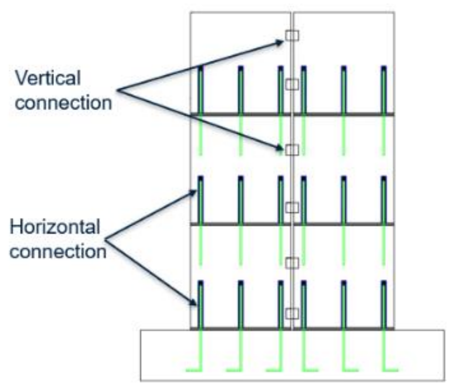
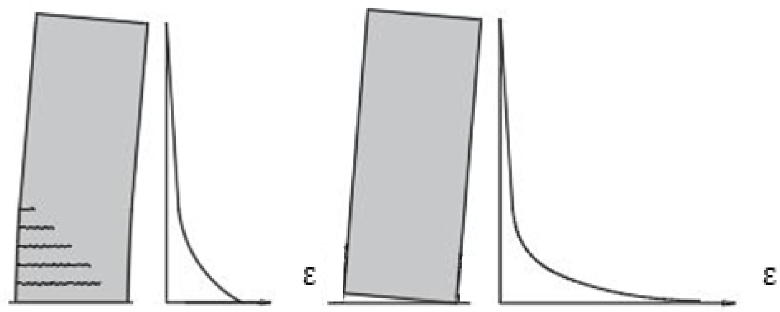


Figure 3. Types of connections in precast concrete wall panels.

The seismic response of precast concrete walls is heavily influenced by the design of their connections. Precast concrete connections can be categorized into three types: emulative, emulative-transition, and jointed. ***Emulative*** connections are designed to have higher strength than the wall panel itself. Strong connections are critical for precast shear walls to achieve similar structural performance as CIP structures. Emulative connections can be applied to structural systems with any system ductility. Shear walls with emulative connections are often analyzed as CIP shear walls [3]. Shear walls with this type of connection results in inelastic deformation occurring mainly in the panel, similar to the plastic hinge region in a CIP shear wall [4]. Connections must be detailed to prevent gap opening and shear slips to achieve emulative behavior. Emulative walls are intended to have CIP reinforced concrete wall behavior, including ductility and energy dissipation during the flexural yielding of wall reinforcement [5]. Similar to CIP walls, there is distributed yielding in the wall panel over a plastic hinge length, see Figure 4a. ***Emulative–Transition*** connections are designed to have approximately the same capacity as the wall panel. Although the inelastic deformation and yielding of reinforcements take place in the wall panel, substantial joint opening still occurs. According to the Structural Engineering Society of New Zealand (INC) in the design basis document GD# 3, for an emulative-transition connection, the rocking at the panel joint is accountable for 50-60% of the lateral deformation [4].

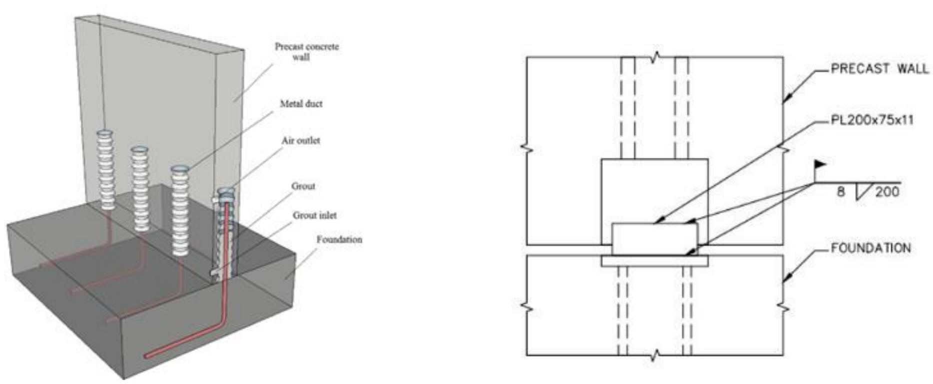
Jointed connections have the yielding occur with a hinge forming at the single crack located at the joint interface seen in Figure 4b. The INC mentions that a connection is considered emulative when its strength is less than 80% of the wall's strength. In a jointed system, the inelastic deformation primarily occurs at the panel joint, and panel reinforcements do not yield. According to INC, walls with these types of connections can have up to 80% lateral deformation caused by the rocking around the panel joint.



(a) *(b)*

Figure 4. System failure modes:(a) Emulative system failure, (b) Jointed system failure.

Connections in precast concrete shear walls are typically chosen based on constructability factors, such as ease of assembly and structural design requirements. Canadian construction's most prevalent horizontal connections include grouted dowel connections (Figure 5a) and welded plate connections (Figure 5b). Grouted dowel connections, characterized by their simplicity and cost-effectiveness, offer adequate strength and stiffness for various applications. However, despite their widespread use, a limited body of research on this connection type indicates potential opportunities for further improvement and optimization. Welded plate connections are popular in Canada and the United States for wall foundation connections, as they effectively align precast elements with CIP elements.



(a) *(b)*

Figure 5. Horizontal connections:(a) Grouted dowel [6], (b) Welded steel plate [1].

Both grouted dowel and welded plate connections can be used to achieve either emulative or jointed connections. In the Canadian context, multi-story buildings typically feature one panel per floor, which presents challenges for emulative connections. With current construction methods, emulative connections using grouted dowel connections with a strong splice covers more than 50% of the wall panel (Figure 3), which may lead to localized yielding. The result may be different ductility levels compared to the intended emulative response. A recent study by Seifi et al. [6] revealed cracks directly above both the interface and the connection in the emulative wall. However, it is important to note that the aspect ratio of the examined panels differs from what is typically used in Canada.

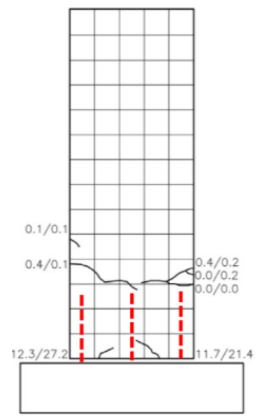


Figure 6. A crack pattern of a wall with grouted dowel connection [6].

Designers may employ unbonded post-tensioning (PT) and energy-dissipating devices for high-performance jointed precast concrete shear walls to achieve a ductile response [4]. Although numerous studies (Smith and Kurama, 2014 [7]; Twigden et al., 2016 [8]; Sritharan et al.; 2015 [9]; Kurama et al. 1999 [10]) have been conducted on this system, it remains relatively uncommon in practice. Nevertheless, some examples of successful implementation include the Case Adelante in San Francisco, California, and the Endoscopy Consultants in Christchurch, New Zealand.

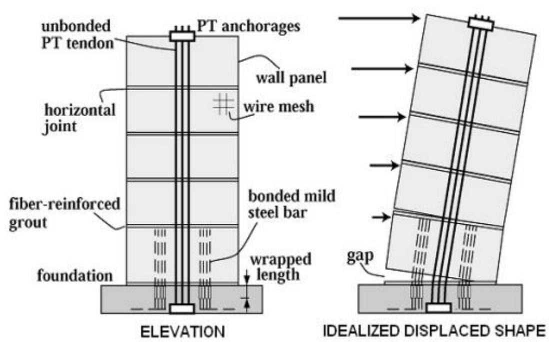


Figure 7. Unbonded PT shear wall connection [7].

CURRENT SHEAR WALLS DESIGN PROVISIONS

Canada, the United States, and New Zealand have similar construction methods for precast concrete shear walls. This section analyzes and discusses each country's current seismic design provisions. By understanding the similarities and differences between these provisions, we can better understand the best practices for designing and constructing precast concrete shear walls. It is important to mention that all three countries' provisions require a minimum of two connections per wall panel for structural integrity.

Seismic design of precast shear walls in Canada

In Canada, the design of precast buildings must follow the NBCC (National Building Code of Canada) 2020 to determine force and deformation demands. Precast shear walls, diaphragms, and connections follow CSA (Canadian Standards Association) A23.3-19 [8]. CPCI is an industry-led not-for-profit, which provides design guidance and education related to precast concrete construction.

In Canadian design, the seismic demand is determined using the Equivalent static force procedure or Modal response spectrum analysis. The demands are then reduced by a ductility-related factor (R_d) and an over-strength-related factor (R_o). The value of R_d and R_o depends on the detailing of the system; lower values of R_d indicate lower system ductility. The NBCC 2020 provides R_d R_o values and seismic category (SC) height limitations for reinforced concrete (RC) shear walls and tilt-up walls designed according to CSA A23.3-19. The notable difference between the RC systems and the tilt-up systems is the height limits; for example, tilt-up conventional walls are not permitted (NP) in SC3 and SC4 and have height limitations in SC1 (25m) and SC2

(20m). However, RC conventional construction shear walls are not limited (NL) to SC1 and SC2, and they have height limits in SC3 (40m) and SC4 (30m).

Table 1. NBCC 2020 Design coefficients and factors for SFRS.

SFRS	R_d	R_o	Height limit [m]			
			SC1	SC2	SC3	SC4
Ductile shear walls	3.5	1.6	NL	NL	NL	NL
Moderately ductile shear walls	2.0	1.4	NL	NL	NL	60
Conventional construction Shear walls	1.5	1.3	NL	NL	40	30
Tilt-up Moderately ductile walls	2.0	1.3	30	25	25	25
Tilt-up Limited ductility walls	1.5	1.3	30	25	20	20
Tilt-up Conventional walls	1.3	1.3	25	20	NP	NP

Tilt-up is a type of onsite precast concrete construction. In this construction method, concrete panels are cast horizontally on a large slab at the site, then lifted into place to form walls able to resist both vertical and lateral loads. Tilt-up construction is a well-defined construction method, with its design guidelines provided in CSA.A23-19 (clause 23) and NBCC 2020. However, due to the height restriction of 30 meters, it is typically used for low-rise commercial and industrial buildings. For multi-story precast concrete shear walls over 30 meters, designers use clauses for shear walls constructed with precast concrete. The detailed requirements for each type of seismic force-resisting system are described below.

Conventional construction precast concrete shear walls

The current CSA A23-19 does not have specific design provisions for conventional precast concrete shear walls. Conventional precast shear walls are designed using Clause 21.6 guidelines for CIP conventional shear walls. However, this clause does not explicitly address precast concrete construction. CSA A23-19 does not provide specifications for whether the walls should be designed as emulative or jointed.

Moderately ductile shear walls constructed with precast concrete

The walls are required to meet the guidelines of CIP moderately ductile shear walls. From ACI 318-19, CSA A23-19 Clause 21.8.4 states that the connection yielding should be limited to steel elements, which implies a jointed connection. If the connections are not designed to yield, they must have 150% of the yield strength of the yielding element [12]. Similar to conventional construction, CSA does not specify if these walls are to be designed as an emulative or jointed system.

Ductile shear walls constructed with precast concrete

Ductile shear walls constructed with precast concrete must meet all the CIP ductile shear walls in CSA A23-19 clause 21.5 and have strong connections. The factored resistance of the strong connection should be higher than the probable resistance at the connection [12]. Therefore, CSA requires ductile precast shear walls to be emulative, unlike moderately ductile and conventional construction precast shear walls.

Seismic design of precast shear walls in the United States

In the United States, the design of precast buildings must follow the American Society of Civil Engineers (ASCE) 7-22 to determine force and deformation demands. Precast shear walls, diaphragms, and connections follow American Concrete Institute (ACI) 318-19. Precast/Prestressed Concrete Institute (PCI) is an industry-led not-for-profit that provides design guidance and education related to precast concrete construction.

The ASCE 7-22 provides response modification factor (R) and overstrength factor (Ω_0^b) values and seismic design category (SDC) height limitations for concrete shear walls designed according to ACI 318-19 and ASCE 7-22 (Table2). There are four concrete shear wall classifications in the United States: ordinary precast concrete shear walls, ordinary reinforced concrete shear walls, intermediate precast concrete shear walls, and special reinforced concrete shear walls, which may be either CIP or precast.

Table 2. ASCE 7-22 Design coefficients and factors for SFRS.

SFRS	R	Ω_0^b	Height limit [ft]				
			SDC B	SDC C	SDC D	SDC E	SDC F
Special RC shear walls	5	2.5	NL	NL	160	160	100
Ordinary RC shear walls	4	2.5	NL	NL	NP	NP	NP
Intermediate precast shear walls	4	2.5	NL	NL	40	40	40
Ordinary precast shear walls	3	2.5	NL	NP	NP	NP	NP

PCI 8th edition states that a dry connection with small grout joints is commonly used in areas with low to moderate seismic activity. In contrast, in regions with high seismic levels, connections between precast walls and foundations are designed to behave like CIP walls or include post-tensioning [8].

ACI 318-19 clause 16.3.3.1 mentions that the factored strength of the connection between walls or between precast elements and foundation (ϕSn) should be equal to or greater than the strength of a member required to resist a load (U).

The design of precast concrete shear walls in the United States is classified into three groups: ordinary precast shear walls, intermediate precast shear walls, and special structural walls constructed using precast concrete.

Ordinary precast shear wall

Ordinary precast shear walls do not have precast-specific seismic detailing and are typically limited to seismic design category B, whereas ordinary reinforced walls can be designed for categories B and C. Additionally, ordinary precast shear walls have a lower response modification factor (R) of 3, less than the value of 4 for ordinary reinforced walls. The ASCE 7-22 recognizes the low ductility of ordinary precast shear walls [15]. It provides R values for ordinary precast concrete shear walls approximately 75% lower than those for ordinary reinforced concrete shear walls.

Furthermore, ACI 318-19 does not have specific seismic provisions for ordinary precast. As a result, these walls are designed using ACI 318-19 guidelines for ordinary reinforced concrete shear walls. It is unclear whether these walls are designed as emulative or jointed, as ACI 318-19 does not provide guidance on detailing the connection for this type of wall.

Intermediate Precast shear wall

Intermediate precast shear walls have higher R than ordinary due to higher ductility detailing requirements. They are permitted to be used in SDC B and C; however, for SDC D, E, and F, they are limited to a height of 40ft (≈ 12m). ACI 318-19 clause 18.5.2 limits the yielding to the connection to reinforcement and steel elements. The recommended strength of the elements not designed for yielding should be 1.5 Sy or higher. Sy is taken as the nominal yield strength of the element with the weakest yielding [16]. This clause is similar to CSA A23-19 clause 21.8.4 for moderately ductile precast shear walls.

Moreover, ASCE 7-2022 requires the connections to maintain 80% of their strength at the deformation generated by design displacement or use type 2 mechanical splices to achieve the code-based deformation requirement without addressing the deformation demand and obtaining 100% of the maximum strength of the reinforcement [15]. Unlike CSA, ACI 318-19 provides a ductility requirement for intermediate precast shear walls. However, as the ACI 318-19 clause 16.3.3.1 states that the connection strength can be equal to or greater than the wall. It is unclear if the walls are designed as emulative or jointed.

Special structural walls constructed using precast concrete

Special structural walls constructed using precast concrete are required to satisfy ACI 318-19 clause 18.10 for CIP special structural walls and clause 18.5.2 for intermediate precast structural walls [16]. Unlike ordinary and intermediate precast concrete shear walls, ASCE 7-22 does not provide an R-value for special precast structural walls.

The most common special precast structural wall is the unbonded PT precast wall. ACI Innovation Task Force 5 created ITG-5.2-09 to provide specific design guidelines and ITG-5.1M-07 to provide guidelines for testing analysis for this type of wall. ACI Innovation Task Force 5 (ITG-5.2-09) states that special precast walls should have a height length ratio equal to or greater than 0.5. The designed walls should be able to rock about the base. The energy dissipation reinforcement should be 25% of the flexural strength of the wall foundation interface [17].

Seismic Design of precast shear walls in New Zealand

In New Zealand, precast concrete shear wall design follows Chapter 18 in the New Zealand Standard (NZS) 3101:2006. NZS 3101:2006 provides a ductility factor (μ) for different types of CIP walls (Table 3); however, there are no specific μ for precast walls. The New Zealand equivalent to R factor equal to μ divided by structural performance factor (Sp); Sp is typically 0.7 for structures with μ greater than 3 and 0.9 for nominally ductile structures.

Table 3. NZS 3101:2006 Structural ductility factor.

Type of structure	μ	R
Nominally ductile walls	1.25	1.4
Limited ductile walls	3	4.3
Ductile walls (two or more cantilevered)	5	7.1
Ductile walls (single cantilever)	4	5.7
Ductile walls (two or more coupled)	6	8.6

New Zealand precast concrete shear walls are divided into two groups: Equivalent monolithic and jointed wall systems, with the primary distinction being their connection design.

Monolithic Walls

Precast concrete structures are designed to achieve the same performance as CIP structures. The connections in these wall panels are designed to be stronger than the wall (i.e., emulative). Therefore, their elastic limit is not surpassed while satisfying the building's ductility demand [19].

The NZS 3101:2006 clause 18.8.4.2.2 classifies monolithic system connections into strong connections of nominal ductility and ductile connections. With strong connections of nominal ductility in structural walls, yielding happens away from the connection due to the capacity design. In contrast, ductile connections consist of longitudinal bars that undergo plastic deformation during a severe earthquake [18].

Jointed Walls

The connection is designed to have a lower capacity than the wall panel. The connection strength is less than 80% of the wall strength. In these connections, inelastic deformation occurs at the panel joint, and panel reinforcements do not yield. The systems can be designed as ductile, have energy dissipation at the interface, and contribute to the building's ductility [19].

Connections in the jointed systems are categorized as connections of limited ductility, ductile jointed connections, or ductile hybrid connections per NZS 3101:2006 clause 18.8.4.3.2. Connections of limited ductility do not perform as a composite of monolithic structures; they typically have limited ductility and can be found in tilt-up construction. The jointed ductile connections are typically unbonded PT tendons connections. These connections allow non-linear deformations to occur primarily at the interface, where a crack can open and close. Additionally, the PT tendons possess a self-centring ability, which helps to minimize damage following an earthquake. Ductile hybrid connections combine unbonded PT tendons, longitudinal steel rebars, or other energy-dissipating devices [18]. Precast walls in New Zealand are currently designed using CIP RC walls guidelines in NZS 3101.1:2006 chapter 11.

DISCUSSION, CHALLENGES, AND FUTURE WORK

This paper highlights the necessity for further research on precast concrete shear walls in New Zealand, Canada, and the United States, given the potential need to investigate and improve current seismic design provisions. The limited experimental data on common construction methods, such as grouted dowel connections, underscores the need for additional experimental investigation.

Seismic design provisions across these countries exhibit similarities, including allowing precast concrete shear wall systems to be designed as ductile or low-ductility systems and permitting jointed and emulative connections. However, the Canadian and New Zealand provisions do not specify seismic force reduction factors for precast shear walls, instead employing the same factors as (CIP) systems. This approach implies equivalent ductility between CIP and precast systems. In contrast, US provisions use lower seismic force reduction factors for precast concrete systems, acknowledging their potentially diminished ductility. There is limited information on ensuring sufficient ductility capacity in jointed connections and confirming that emulative connections genuinely replicate the behavior of CIP walls. Further research and investigation are needed to address this and refine the seismic design provisions for precast concrete shear wall systems.

Numerical studies are also required to determine the appropriateness of seismic force reduction factors, which have yet to be verified through any study. Moreover, unanswered questions remain for emulative precast concrete shear walls with non-jointed connections, such as the appearance of plastic hinge lengths when numerous splices exist throughout each connection. A comprehensive investigation is essential to better understand the ductility and performance of precast concrete shear walls in seismic conditions. Other potential research topics include hollow-core slabs, jointed shear walls in high-rise buildings, and flanged walls.

Hollow-core Slab

The hollow-core slab is the most commonly used floor system in precast concrete. The performance behavior of the hollow core slab is essential to the performance of boarding wall panels. However, according to Corney et al. (2021), based on the super-assembly and subassembly tests done in New Zealand, there are various potential failure modes for hollow-core floor systems [20].

Loss of support failure in precast concrete hollow-core slabs can cause floor deformation, which depends on the bearing surface. Adequate seating length is essential to prevent this failure. Slabs supported by mortar pads or bare concrete risk non-ductile positive moment failure at the slab edge, which can be averted using low-friction bearing strips. Non-ductile negative moment failure can also occur, typically at the slab support. Web-splitting failure, caused by vertical beam displacement, can lead to a partial floor collapse when a hollow-core slab connects to a concrete beam. Figure 8 demonstrates hollow-core slab failure.

Figure 8. Hollow-core unit after the Northridge earthquake [20]

NZS 3101.1:2006 A3 has provisions to mitigate issues associated with hollow-core slabs. Clause 18.7.4.3 sets a minimum requirement for seating of 75 mm; this prevents the loss of seating failure. Moreover, the code recommends linking slab to prevent positive moment failure due to web splitting [18].

Although measures have been taken in New Zealand to address this issue, limited research has been conducted in Canada and the US. Furthermore, in New Zealand construction, moment frames are connected to walls with beam elongation. It is uncertain how these precast concrete hollow-core slabs will behave in buildings with many walls, as is often the case in Canada.

Jointed shear walls in High-rise Buildings

There has been limited research into the seismic behavior of jointed precast shear walls and coupled walls in high-rise buildings. In particular, there is potential for these walls may experience large flexural strains over their height after hinging at the base connection due to high modes [21-22]. The higher modes are crucial, and it is necessary to develop effective mitigation strategies to limit damage in the event of an earthquake. Multiple rocking joints [23-24] could be a potential solution to address higher mode demands. Although some research has been conducted on precast coupled walls in low-rise buildings, there is a need for further research on the inelastic response of precast coupled walls in high-rise buildings that use jointed connections. Such research would help to identify the most effective seismic design strategies for these systems.

Flanged walls

Most studies in precast concrete shear walls focus on planar wall systems without examining flanged walls typically used in CIP. Of the studies completed, researchers focused primarily on emulative horizontal connections [25-27]. For example, Sun et al. (2019) [25] explored the cyclic response of H-shaped precast flanged walls with steel bolted connections, which were strong and ductile but also prone to misalignment. Another study by Li et al. (2019) [28] suggested a T-shaped flanged wall with a precast concrete web and CIP flange, which showed similar cyclic behavior to fully CIP construction. However, combining precast and CIP construction may require additional trades onsite, leading to longer construction times. Menegon et al. (2020a, 2020b) [29-30] tested a precast core designed for low-rise buildings in low-seismic zones, which utilized welded plates to connect wall panels and dissipate energy through damages in the wall. However, the construction of these walls required most of the core to be built and shipped to the site, making it unsuitable for high-rise buildings that require larger cores that are too bulky to ship.

Further, there is limited information on jointed flanged walls with practical connections. Potential future research could focus on jointed flanged walls with practical connections that can be integrated with a core wall at both the strong corner and jointed horizontal connections. It would make precast concrete more desirable in regions of high seismicity where higher demands must be resisted.

CONCLUSION

This paper examines precast concrete shear walls' design and construction methodologies in Canada, the United States, and New Zealand. The review reveals that the design codes in these countries would benefit from a thorough experimental and numerical investigation into the seismic performance of such systems. Currently, experimental and numerical studies are scarce on the seismic response of conventionally constructed precast walls in all three nations. Consequently, it is crucial for future research to target and bridge these knowledge gaps, to enhance seismic design provisions for precast concrete shear walls. This will ultimately ensure the implementation of safe, efficient, and robust construction techniques that cater to the needs of residential and commercial structures across the globe.

REFERENCES

[1] CPCI Design Manual 5 - secured - 11 30 2017.pdf - CPCI design manual 5th edition structural/ Architectural CPCI Design manual 5th edition precast and: Course hero. CPCI Design Manual 5 - SECURED - 11 30 2017.pdf - CPCI DESIGN MANUAL 5th Edition Structural/ Architectural CPCI DESIGN MANUAL 5th Edition Precast and | Course Hero. (n.d.). Retrieved April 6, 2023, from https://www.coursehero.com/file/36982430/CPCI-Design-Manual-5-SECURED-11-30-2017pdf/

[2] Zaid, M. (2016). *Precast concrete panels as shear walls*. photograph.

[3] ACI 550.1R-09, Guide to Emulating Cast-in-Place Detailing for Seismic Design of Precast Concrete Structures American Concrete Institute / 01-Feb-2009 / 21 pages.

[4] Structural Engineering Society New Zealand (INC). (2021). Precast Concrete - Grouted Connections And Drossbachs - Sesoc Guidance. Structural Engineering Society New Zealand (INC).

[5] Wu, L., Tian, Y., Su, Y., & Chen, H. (2018). Seismic performance of precast composite shear walls reinforced by concrete-filled steel tubes. In Engineering Structures (Vol. 162, pp. 72–83). Elsevier BV. https://doi.org/10.1016/j.engstruct.2018.01.069

[6] Seifi, P., Henry, R. S., & Ingham, J. M. (2019). In-plane cyclic testing of precast concrete wall panels with grouted metal duct base connections. In Engineering Structures (Vol. 184, pp. 85–98). Elsevier BV. https://doi.org/10.1016/j.engstruct.2019.01.079

[7] Smith, B. J., & Kurama, Y. C. (2014). Seismic design guidelines for solid and perforated hybrid precast concrete shear walls. In PCI Journal (Vol. 59, Issue 3, pp. 43–59). Precast/Prestressed Concrete Institute. https://doi.org/10.15554/pcij.06012014.43.59

[8] Twigden, K. M. (2016). In *Dynamic response of unbonded post-tensioned concrete walls for seismic resilient structures*.

[9] Sritharan, S., Aaleti, S., Henry, R. S., Liu, K.-Y., & Tsai, K.-C. (2015). Precast concrete wall with end columns (PreWEC) for earthquake resistant design. In Earthquake Engineering & Structural Dynamics (Vol. 44, Issue 12, pp. 2075–2092). Wiley. https://doi.org/10.1002/eqe.2576

[10] Kurama, Y., Pessiki, S., Sause, R., & Lu, L.-W. (1999). Seismic Behavior and Design of Unbonded Post-Tensioned Precast Concrete Walls. In PCI Journal (Vol. 44, Issue 3, pp. 72–89). Precast/Prestressed Concrete Institute. https://doi.org/10.15554/pcij.05011999.72.89

[11] Canadian Precast /Prestressed Concrete Institute. (n.d.). *CPCI Technical Information Bulletin: Total Precast Concrete High-Rise Construction and Provincial Building Codes*.

[12] CSA (Canadian Standards Association) A23.3-19, Design of concrete structures, 2019

[13] National Research Council Canada. (2022). *National building code of Canada 2020*.

[14] PCI Industry Handbook Committee. PCI design handbook: Precast and prestressed concrete. 8th ed. Chicago, IL: Precast Concrete Institute, 2022

[15] (ASCE), A. S. of C. E. (2022). *Minimum design loads and associated criteria for buildings and other structures*. American Society of Civil Engineers.

[16] American Concrete Institute. (2022). *Building code requirements for structural concrete (ACI 318-19): An ACI Standard; commentary on building code requirements for structural concrete (ACI 318R-19).*

[17] American Concrete Institute. (2009). *Requirements for design of a special unbonded post-tensioned precast shear wall satisfying Aci Itg-5.1 (Aci Itg-5.2-09) and commentary: An Aci standard*.

[18] NZS (New Zealand Standard), NZS 3101.1:2006 NZS 3101.2:2006, Concrete structures standard, 2017

[19] Bull, D. K. (1999). *Guidelines for the use of structural precast concrete in buildings: Report of a study group of the New Zealand Concrete Society and the New Zealand Society for Earthquake Engineering*. Univ. of Canterbury, Center for Advanced Engineering.
[20] Corney, S. R., Puranam, A. Y., Elwood, K. J., Henry, R. S., & Bull, D. (2021). Seismic performance of precast hollow-core floors: Part 1—experimental data. *ACI Structural Journal*. https://doi.org/10.14359/51732821
[21] Tobber, L. (2021). Development of an innovative earthquake-resilient reinforced concrete core wall. Retrieved from UBC circle
[22] Tobber, L., Yang, T.Y. (2021). Design of Controlled outriggered rocking wall using Equivalent energy design procedure. Engineering Structures
[23] Wiebe, L., & Christopoulos, C. (2009). Mitigation of Higher Mode Effects in Base-Rocking Systems by Using Multiple Rocking Sections. Journal of Earthquake Engineering, 13(sup1), 83– 108. https://doi.org/10.1080/13632460902813315
[24] Khanmohammadi M., Heydari S. (2015). Seismic behaviour improvement of reinforced concrete shear wall buildings using multiple rocking systems. Engineering Structures 100: 577–589. doi:10.1016/j.engstruct.2015.06.043
[25] Sun, J., Qiu, H., Lu, Y., & Jiang, H. (2019). Experimental study of lateral load behaviour of H-shaped precast reinforced concrete shear walls with bolted steel connections. The Structural Design of Tall and Special Buildings, 28(15). https://doi.org/10.1002/tal.1663
[26] Sun, J., Qiu, H., & Jiang, H. (2018). Experimental study and associated mechanism analysis of horizontal bolted connections involved in a precast concrete shear wall system. Structural Concrete, 20(1), 282–295. https://doi.org/10.1002/suco.201800113
[27] Sun, J., Qiu, H., & Lu, Y. (2016). Experimental study and associated numerical simulation of horizontally connected precast shear wall assembly. The Structural Design of Tall and Special Buildings, 25(13), 659–678. https://doi.org/10.1002/tal.1277
[28] Li, J., Fan, Q., Lu, Z., & Wang, Y. (2019). Experimental study on seismic performance of T-shaped partly precast reinforced concrete shear wall with grouting sleeves. The Structural Design of Tall and Special Buildings, 28(13). https://doi.org/10.1002/tal.1632
[29] Menegon, S. J., Wilson, J. L., Lam, N. T. K., & Gad, E. F. (2020). Experimental testing of innovative panel-to-panel connections for precast concrete building cores. Engineering Structures, 207, 110239. https://doi.org/10.1016/j.engstruct.2020.110239
[30] Menegon, S. J., Wilson, J. L., Lam, N. T., & Gad, E. F. (2020b). Experimental assessment of the ultimate performance and lateral drift behaviour of precast concrete building cores. Advances in Structural Engineering, 23(12), 2597–2613. https://doi.org/10.1177/1369433220919077