Seismic Performance of Precast RC Walls in Australia: Literature Review

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Abstract

In Australia, precast reinforced concrete walls have been increasingly used as lateral-load-resisting elements due to their fast construction speed, reduced waste, and better quality. This paper summarises the typical detailing of Australia's precast RC structural walls and highlights the experimental and numerical studies of precast RC walls adopting grout tube connections and welded stitch plates. According to the literature review, precast walls with grout tube wall-foundation connections typically deflect in a rocking manner under reversed cyclic loads. In laboratory experiments, a gap opening and a single crack are generally observed at the wall base, with a concentration of plastic deformation. The typical failure mode is the fracturing of connecting dowels. Since there has been little research investigating the numerical modelling of these walls, it will be the focus of future research of the authors.

Keywords: precast reinforced concrete walls; grout tube connections; welded stitch plates.

1 Introduction

The early history of precast concrete in Australia can be traced back to the 1900s. In that era, precast concrete had more applications in the construction of pipes and sea walls (National Precast Concrete Association Australia [NPCAA] & Concrete Institute of Australia [CIA], 2009). Over the last few decades, precast products, such as precast concrete finishes, cladding, partitions, and floors, are becoming popular in Australia due to their better quality, reduced waste, and faster on-site construction (Menegon et al., 2020a; NPCAA & CIA, 2009). Notably, there has been an increasing number of loadbearing precast reinforced concrete (RC) walls used in low-to-medium rise buildings in Australia in recent years (Menegon et al., 2017b).

As precast structural members are manufactured individually in a factory, their installation and assembly at a construction site are crucial in guaranteeing the overall structural integrity and safety. It has been observed from studies and past earthquakes that the behaviour of connections between precast elements can control the overall structural behaviour of buildings

(Federal Emergency Management Agency [FEMA], 2006; International Federation for Structural Concrete [fib], 2008; Kurama et al., 2018; Park, 1995). Depending on connection details, a precast RC structure can be categorised into the equivalent monolithic system or jointed system (Park, 2003). In the equivalent monolithic system, structural elements are assembled at a construction site by emulative connections, such as grouted ducts or bonded post-tensioned tendons (Kurama et al., 2018; Park, 2003). As the name suggests, the equivalent monolithic system aims to emulate a comparable cast-in-place construction (Kurama et al., 2018). The emulative connections can be designed to be strong (i.e., limited ductile) or ductile. The capacity design approach is generally employed for the strong connections to avoid the yielding of connections under earthquake loading. However, a ductile connection should be designed with sufficient ductility to sustain its resistance after yielding (Park, 2003). However, the equivalent monolithic system may still exhibit different structural responses during earthquakes from a cast-in-place construction if the precast structure is not well detailed (Seifi et al., 2016; Wibowo et al., 2010). Unregulated construction practices, such as insufficient grouting of connections or eccentrically placing connecting bars in grouted ducts, can also impair the seismic performance of precast buildings (Cao & Li, 2019; Provost-Smith et al., 2019; Xu et al., 2018).

By contrast, a jointed system can have distinct structural behaviour from a cast-in-situ structure. In this system, precast elements are generally connected by dry joints, such as welding, bolting, embedded steel plates or unbonded post-tensioned tendons (Park, 2003). Since dry joints typically have less capacity and stiffness than adjoining structural elements (Park, 2003), inelastic deformation can be concentrated at connections under earthquake excitation (Kurama et al., 2018). As a way to enhance the ductility of the connections, structural members can be connected by unbonded post-tensioned tendons along with extra energy-dissipating devices, such as steel plates or mild steel bars (Kurama, 2005; Park, 2003). A well-known example is the hybrid precast wall with unbonded post-tensioned tendons and flexure steel plates tested in the PRESSS (Precast Seismic Structural Systems) program (Priestley et al., 1999). The self-centring capacity of unbonded post-tensioning tendons helped reduce the damage levels of precast RC walls under earthquake actions and the residual deformation. Also, the application of steel plates in the horizontal joints between walls promoted the energy dissipation capacity of structures (Priestley et al., 1999).

Precast RC structures have been intentionally studied for some decades. The cooperated PRESSS program in the 1990s between the United States and Japan is one of the earliest studies in this field. This program evaluated the structural behaviour of advanced precast structural frames and walls under seismic loading (Priestley, 1991). Later, between 2009 and 2012, European countries collaborated on the SAFECAST project and mainly investigated the behaviour of connections between precast elements (Toniolo, 2013). However, research outcomes obtained in other countries cannot be directly applied to Australia's precast buildings without thorough investigation. Depending on the adopted design principles and detailing of elements and connections, precast structures can behave uniquely under seismic loading and may exhibit distinct levels of vulnerability in earthquake events (FEMA, 2006; Magliulo et al., 2014). Also, applications of some advanced precast structural systems may not be cost-effective for Australia, a low-to-moderate seismicity region.

Due to the relatively short history of precast RC structural walls in Australia, there is a paucity of research evaluating their seismic performance and vulnerability. More experimental and numerical investigations are necessary and valuable to help the engineering community better comprehend this structural system in Australia. Therefore, the authors proposed a multi-phase research project to bridge the knowledge gaps and provide an insight into the seismic performance and potential deficiencies of typical precast RC wall buildings in Australia. As an initial step, the authors conducted a literature review about typical Australia's precast RC structural walls, particularly the walls incorporating grout dowels and welded stitch plates, which have been identified as the common connections in Australia's precast walls (Menegon et al., 2017b, 2020a). This paper presents the review outcomes and a plan for future research.

2 Design and construction of precast RC walls in Australia

2.1 General design principles of precast RC buildings in Australia

Similar to cast-in-situ RC elements, the design and construction of precast concrete elements should follow the *National Construction Code* (Australian Building Codes Board, 2020). Some local authorities also require using *AS 3850:2015 Prefabricated Concrete Elements* (Standards Australia, 2015a, 2015b) in a precast building project. The AS 3850 series specifies the general design, manufacture, transportation, and construction requirements for precast concrete elements. As per AS 3850.2 (Standards Australia, 2015b), the design of precast elements has two stages: the erection design and the in-service design stage. The erection design deals with the safety of structures in the construction phase. Engineers should predict and assess temporary transportation, installation, and construction forces before structural elements have been reliably connected (Standards Australia, 2015b). Also, precast members, shoring, bracing, and lifting systems are generally required to be tested before the on-site construction per AS 3850.1 in order to avoid unexpected deficiencies (Standards Australia, 2015a).

In the in-service design, precast elements are treated as permanent structural components. Like a cast-in-place structure, engineers should design the permanent precast structure per AS 3600 or AS 4100 with a consideration of constructability (Standards Australia, 2015b). However, designing a precast building based on standards initially prepared for cast-in-place structures could be inappropriate (Elsayed & Nehdi, 2017; Hemamalini et al., 2021). For example, Steuck et al. (2009) found that the embedment length of connecting dowels in precast walls calculated using standards written for traditional reinforcement is almost three times larger than the length needed to develop the same dowel stress in experimental testing. Also, some studies have underlined the significance of the capacity design in controlling the yielding mechanism of precast structures under earthquakes (Park, 2003; Menegon et al., 2018). However, current Australian standards have not covered this design philosophy or specified a similar approach (Menegon et al., 2018).

The Australian concrete industry also provided guidelines and design handbooks for precast structures. For example, NPCAA and CIA (2009) published the *Precast Concrete Handbook*, clearly explaining Australia's precast concrete elements, their history, design principles, fabrication, and installation. Cement and Concrete Aggregates Australia (2001) also provided guidelines on the design and construction of precast concrete panels, including loadbearing precast walls, in houses or multi-storey residential buildings.

2.2 Typical detailing of loadbearing precast RC walls in Australia

Solid precast RC structural walls have been used in multi-story buildings in Australia for loadbearing purposes (Menegon et al., 2017b; NPCAA & CIA, 2009). Rectangular precast panels can be joined together to behave as L-, U- or box-shaped cores to resist lateral loads (Menegon et al., 2020a; NPCAA & CIA, 2009). In medium-rise buildings, it is also common to use a hybrid system with central cast-in-place RC cores as lateral-load-resisting elements and peripheral precast walls as gravity-load-resisting elements. However, it can be problematic to neglect the lateral loads acting on the perimeter precast walls, which have considerable stiffness and are restrained by rigid slabs (Menegon et al., 2018).

Similar to cast-in-place RC walls, the dimensions of precast walls should be designed to satisfy functional and structural requirements. However, the sizing of precast walls should also conform to the transportation limits required by road authorities and the lifting capacity of on-site cranes (NPCAA & CIA, 2009). According to NPCAA & CIA (2009), precast panels are typically one- to two-storey high and less than 3 to 3.5 m wide, primarily depending on architectural and structural requirements as well as transportation regulations. The minimum thickness of the walls is 125 mm to 150 mm so as to ensure the stipulated fire resistance levels and sufficient cover to reinforcement. If the thickness exceeds 175 mm, precast walls should have two layers of reinforcement.

As a typical practice in Australia, N40 or N50 concrete is used to cast precast concrete walls. These walls may have a single layer or two layers of L-grade mesh. The ends of the walls commonly have two N-grade vertical trimmer bars (Menegon et al., 2017b). According to Menegon et al. (2018), precast walls with a central layer mesh are more prevalent in existing buildings. However, it should be noted that a single layer mesh is no longer acceptable to be used in limited ductile walls per AS 3600:2018 (Standards Australia, 2018). In precast walls with two layers of mesh, extra D500N vertical bars can also be placed between mesh to enhance the load-carrying capacity (Menegon et al., 2017b), as shown in Figure 1.

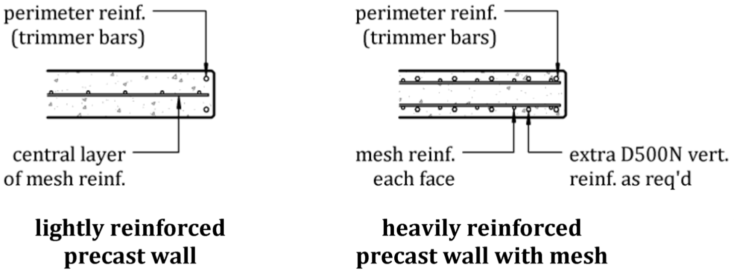
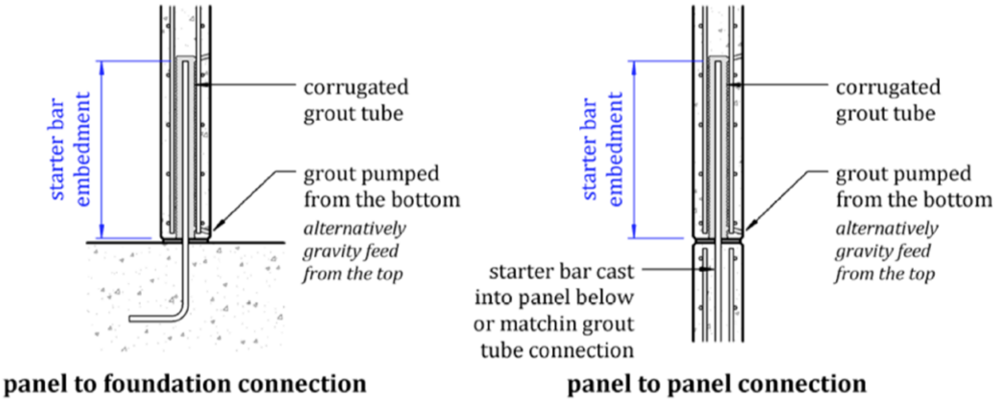


Figure 1. Typical detailing of precast RC walls in Australia (Menegon, 2018)

Note. From *Displacement Behaviour of Reinforced Concrete Walls in Regions of Lower Seismicity*, by Scott J. Menegon, 2018. Copyright 2018, Scott J. Menegon.

2.3 Typical wall-foundation and horizontal wall-wall connections in Australia

A typical type of wall-foundation and horizontal wall-wall connection (i.e., assembling walls at different levels) in Australia is the grout tube connection (Menegon et al., 2020a), as illustrated in Figure 2. This connection has been widely used in precast walls, bridge columns and bent caps in several countries (Mashal et al., 2016; Matsumoto et al., 2002; Seifi et al., 2016). It is also called the 'grouted dowel' (Elsayed et al., 2019) or 'grouted duct connection' (Seifi et al., 2016). When casting a precast panel in a factory, corrugated ducts, usually made up of metal, are embedded in the bottom of the panel, with a spacing commonly larger than vertical reinforcement in the wall (Seifi et al., 2016). The internal diameter of ducts is typically at least three times the dowel diameter (NPCAA & CIA, 2009). In Australia, D500N deformed bars are used as connection dowels if precast walls are designed as limited ductile walls (Menegon et al., 2018). The dowel development length can be calculated following the same approach for traditional reinforcing bars in concrete (Menegon et al., 2020a). Some researchers also recommended having a clear spacing of not less than 75 mm between the top end of dowels and ducts to mitigate the adverse impact of water bleeding (Crisafulli et al., 2002). It is not sure if this detailing has also been adopted in Australia.



panel to foundation connection

panel to panel connection

Figure 2. Typical grout tube connections in Australia (Menegon, 2018)

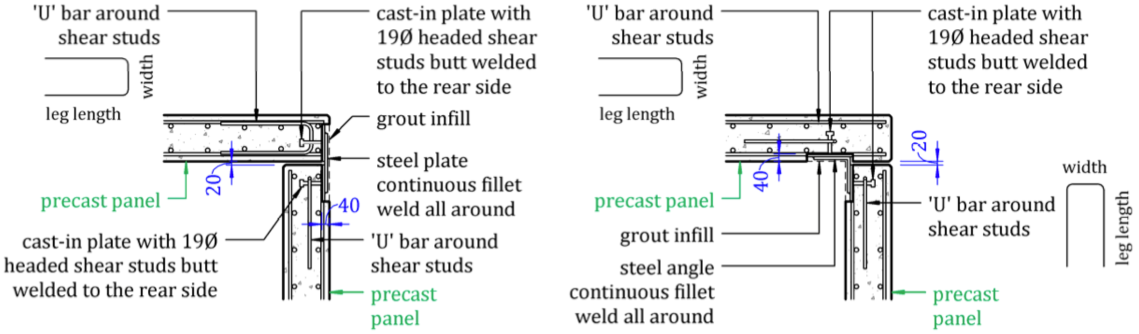
Note. From *Displacement Behaviour of Reinforced Concrete Walls in Regions of Lower Seismicity*, by Scott J. Menegon, 2018. Copyright 2018, Scott J. Menegon.

When erecting a precast wall at a construction site, dowels protruding from the cast-in-place foundation or the lower wall are inserted into ducts in the upper wall (Menegon et al., 2017b; NPCAA & CIA, 2009; Seifi et al., 2016). A small gap, namely the bedding layer, is left between two elements by packing material for alignment (Hemamathi & Jaya, 2021; Kurama et al., 2018; Seifi et al., 2019). The gap is dry packed with grouts first. On the second day, high-strength, non-shrink and flowable grouts are pumped into the ducts to allow effective load transfer between elements (Menegon et al., 2018, 2020a; NPCAA & CIA, 2009). Typically, the grout compressive strength is 10 to 20 MPa higher than the concrete strength of precast walls (Menegon et al., 2018). In Australia, it is common to pump grouts into an inlet tube at the top of a duct (i.e., 'gravity fill') (Menegon et al., 2020a). However, this approach may cause air entrapment in the duct if grouting operations are not regulated. Instead, it is recommended to pour grouts into the bottom of a duct until the grouts run out of an outlet tube at the top (Crisafulli et al., 2002; Menegon et al., 2020a; Seifi et al., 2019).

The total area of connecting dowels may occasionally be smaller than that of the vertical reinforcement in a precast wall (Menegon et al., 2020a). A possible reason is that the minimum wall reinforcement content stipulated in standards can be greater than the dowels needed to attain design strength. This detailing can result in a critical section forming at the interface between elements, with a concentration of deformation under lateral loads (Menegon et al., 2020a; Seifi et al., 2019). In this case, it is more appropriate to design the precast concrete panel as a non-ductile wall (Menegon et al., 2018).

2.4 Typical vertical wall-wall connections in Australia

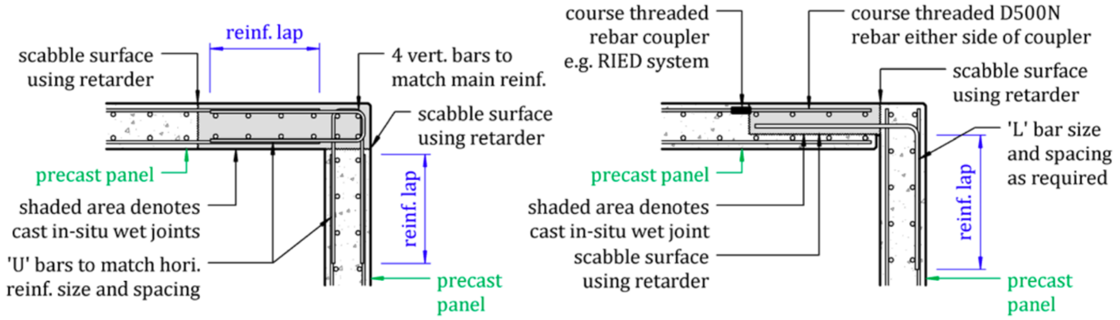
Adjacent precast walls at the same level can be connected by welded stitch plates (WSP) or wet joints (i.e., emulative connections) (Menegon et al., 2017b). Figure 3 illustrates an example of WSP used in Australia. In factories, steel plates (i.e., cast-in plates) are embedded in a precast panel with shear studs welded to the plates to provide resistance. U-shaped reinforcing bars are placed around studs for anchorage. At a construction site, stitch plates are welded to the cast-in plate in each precast panel to join two adjacent walls (Menegon et al., 2020b). In this way, the connection can transfer shear force between elements and develop a composite action to withstand lateral loads (Menegon et al., 2020a, 2020b). Alternatively, two precast panels can be connected by wet joints (Menegon et al., 2017b). Reinforcing mesh protruding from a precast wall is spliced with mesh in the adjoining panel through a cast-in-place concrete joint, as shown in Figure 4. Wet joints are generally stronger than WSP, enabling a greater load transfer between elements. However, compared to WSP, constructing a wet joint typically requires more time and cost. Hence, contractors sometimes still prefer to utilise WSP as the vertical wall-wall connection (Menegon et al., 2017b).



outside fixed stitch plate **inside fixed stitch plate**

Figure 3. Examples of typical welded stitch plate connections in Australia (Menegon, 2018)

Note. From *Displacement Behaviour of Reinforced Concrete Walls in Regions of Lower Seismicity*, by Scott J. Menegon, 2018. Copyright 2018, Scott J. Menegon.



wet joint - example 1 **wet joint - example 2**

Figure 4. Typical wet joints in Australia (Menegon, 2018)

Note. From *Displacement Behaviour of Reinforced Concrete Walls in Regions of Lower Seismicity*, by Scott J. Menegon, 2018. Copyright 2018, Scott J. Menegon.

3 Experimental studies of the lateral behaviour of precast RC walls with grout tube wall-foundation connections

3.1 Precast RC structural cores S03, S04 and S05 (Menegon et al., 2020a)

Menegon et al. (2020a) evaluated the in-plane lateral behaviour and failure mechanisms of typical Australia's precast RC structural cores under uniaxial quasi-static cyclic loads. The experimental tests included three box-shaped precast RC cores (S03, S04, and S05). Each core was formed by connecting four rectangular precast panels through WSP and fixed to the foundation and the top boundary element by grout tube connections. All three cores were 2600 mm high and had a width and length of 1200 mm. Cores S03 and S04 had a wall thickness of 130 mm, while S05 was 150 mm thick. All the precast panels were heavily reinforced with two layers of D500L reinforcing mesh. Extra D500N vertical reinforcing bars were placed in S03 and S04 between the reinforcing mesh (Menegon et al., 2020a). The detailing of the specimens implies that these precast cores would exhibit higher capacity under seismic loads than the more common lightly reinforced precast walls in most existing buildings in Australia.

According to experimental results, the ultimate drift ratios of S03, S04 and S05 corresponding to the occurrence of lateral load failure (i.e., 20% drop in lateral strength) were 2.4%, 3.0%, and 1.1%, respectively (Menegon et al., 2020a). After the ultimate displacement, the precast cores still had considerable residual capacity in resisting loads before the wholesale axial load failure. However, Menegon et al. (2017a, 2020a, 2020b) noticed that precast cores exhibited lower stiffness and reduced moment resistance than the comparable cast-in-place RC specimen. Strength degradation of the precast cores was observed after the yielding of wall vertical reinforcement (Menegon et al., 2020a). Also, they found that WSP was not rigid enough in developing full composite resistance. Consequently, only about 80 per cent of the theoretical maximum lateral strength was developed in the precast cores (Menegon et al., 2020b). The flexibility of WSP was also recognised by Hofheins et al. (2002) in their experimental program. Their WSP specimens even experienced a brittle failure. Furthermore, by converting the experimental results to an equivalent single-degree-of-freedom response, Menegon et al. (2020a) found that the overstrength and ductility factor of the four-storey core corresponding to the specimen S05 were only 1.1 and 1.3, respectively. However, when designing S05, they used an overstrength factor of 1.3 and a ductility factor of 2.0 per AS 1170.4 (Standards Australia, 2007). This discrepancy indicates that the design actions of such precast cores might be underestimated if the walls are assumed to have limited ductility.

Specimens S03 and S04 had an average wall vertical reinforcement ratio (i.e., the mean value of vertical reinforcement ratio of four panels in each core) of approximately 1.8% and 3.0%, respectively. However, the average connection reinforcement ratio of S03 and S04 was only about 1.2% (Menegon et al., 2020a). This detailing led to a concentration of plastic strains at the core base. A single crack was observed by Menegon et al. (2020a) across the wall bedding layer when the loads exceeded the grout tensile strength. Therefore, under uniaxial reversed cyclic loads, rocking dominated the lateral displacement of these two precast cores. Although this rocking behaviour enabled the cores to deflect without axial load failure under a large lateral drift, it made the structure vulnerable to torsional actions (Menegon et al., 2020a). Also, in the experimental tests, Menegon et al. (2020a) observed a premature failure of precast cores S03 and S04, namely the fracturing of connection dowels and splitting of concrete in the compression flange. However, a distinct failure mode was observed in the specimen S05. Since S05 had a dowel reinforcement ratio (about 1.5%) greater than the wall vertical reinforcement ratio (about 1.1%), the amount of rocking was significantly reduced. S05 eventually failed due to the fracturing of low ductile wall vertical reinforcement above the base connection. Another study by Wilson et al. (2008) further highlighted that the rocking of precast walls induced excessive shear forces in connections between walls and slabs. If these connections are not detailed for the rocking behaviour, structures may undergo undesirable localised damage during earthquakes.

The experimental study by Menegon et al. (2020a) is valuable to help the engineering community understand the seismic behaviour and potential vulnerability of precast RC walls in Australia. Further research is warranted to investigate the out-of-plane behaviour and the effects of torsional actions on such structural elements. Also, it is necessary to extend the research to precast RC walls with low reinforcement content and a single layer of low ductility mesh, which have been commonly adopted in existing Australian buildings.

3.2 Rectangular precast RC Wall 1 to Wall 7 (Seifi et al., 2019)

Similarly, Seifi et al. (2019) investigated the in-plane lateral response of rectangular precast RC walls with grout tube wall-foundation connections. The specimens were designed to represent typical New Zealand precast walls, which had similar detailing to Australia's practice. As summarised in Table 1, seven precast specimens with varying dimensions and reinforcement content were tested under uniaxial reversed cyclic loads. Specifically, Wall 4 had two layers of reinforcing mesh, while other walls had only one central layer mesh. The wall reinforcement and connecting dowels had a strain corresponding to the peak strength of about 0.10 to 0.12. Also, Wall 5 to Wall 7 were subject to an additional axial load of $0.05A_gf'_c$, but no extra vertical load was applied to other specimens besides their self-weight (Seifi et al., 2019).

Table 1. Details of rectangular precast RC wall specimens (Seifi et al., 2019)

Specimen	Dimensions (Length*Height*Thickness) (mm)	Dowel Reinforcement Ratio	Wall Vertical Reinforcement Ratio	Stirrups around grouted dowel connections
Wall 1	1000 * 3000 * 150	0.40%	0.38%	No
Wall 2	1000 * 3000 * 150	0.40%	0.38%	Spiral stirrups
Wall 3	1000 * 3000 * 150	0.40%	0.38%	Rectangular stirrups
Wall 4	1000 * 3000 * 200	0.30%	0.57%	No
Wall 5	1000 * 3000 * 150	0.40%	0.38%	No
Wall 6	2000 * 4000 * 150	0.34%	0.34%	No
Wall 7	2000 * 4000 * 150	0.34%	0.34%	Rectangular stirrups

As observed in experimental testing, the rocking mechanism dominated the lateral response of Seifi et al. (2019) Wall 1 to Wall 5. In particular, rocking contributed to more than 90% of the lateral deformation of Wall 4 because this wall had a vertical reinforcement ratio of 0.57% while only a 0.30% connection reinforcement ratio. Interestingly, although Wall 1 to 3 and 5 had a dowel reinforcement ratio slightly larger than the wall vertical reinforcement ratio, a significant amount of rocking was still measured by Seifi et al. (2019). The rocking of walls caused a noticeable gap opening at the wall bedding layer, with only minor cracks detected across the bottom regions of the panels. The rocking behaviour also led to reduced stiffness and pinched hysteretic curves of the walls (Seifi et al., 2019). A similar cracking pattern and deformation behaviour was observed by Crisafulli et al. (2002) in their test on a rectangular precast wall. It is worth mentioning that although Wall 5 has the identical dimension and detailing to Wall 1, Seifi et al. (2019) observed less rocking and fewer cracks in Wall 5 attributed to the additional axial load on the wall. Moreover, as Wall 6 had a larger dimension than Wall 5, the amount of rocking was further reduced. As a result, flexural deformation of the wall dominated the lateral response. Similarly, a great amount of flexural deformation was measured in Wall 7 by Seifi et al. (2019), which had the same dimension and axial load ratio as Wall 6. However, since extra rectangular stirrups were placed at the connection region of Wall 7, the development of cracks on the wall was effectively limited at large loading levels. After about a 0.7% drift ratio, rocking became the primary lateral deformation of Wall 7, as reported by Seifi et al. (2019). Also, they detected sliding at the wall base in all specimens, but less than 10% of total lateral deformation in most cases. Sliding was only noticeable at large drifts after the yielding of connecting dowels. However, sliding was significantly decreased when additional axial loads were applied to walls, as observed by Seifi et al. (2019) in Wall 5 to Wall 7.

Finally, Wall 1 to Wall 4 failed because of the fracturing of dowels at the drift ratio of about 2.0%. Since Wall 5 had reduced rocking and sliding compared to the previous four walls, lateral load failure was initiated by the spalling of concrete at extreme compression fibre at about 2.1% drift level. By further increasing the lateral loads, Seifi et al. (2019) observed the fracturing of dowels at roughly a 3.5% drift ratio. Wall 6 experienced more significant concrete spalling at compression toes than Wall 5. The concrete spalling even caused the pull-out failure of the outermost ducts. The ultimate drift of Wall 6 was only 1.5% (Seifi et al., 2019). Seifi (2018) argued that the duct pull-out might be associated with the increased length of Wall 6. Although Wall 7 also had extensive spalling of concrete, the extra confining stirrups in Wall 7 effectively limited the extension of concrete spalling at large drift levels. The wall eventually failed due to the fracturing of connection dowels at a 1.2% drift ratio (Seifi et al., 2019). The Structural Engineering Society New Zealand (SESOC) (2019) also recognised the benefit of providing stirrups around grout tube connections. SESOC further recommended debonding dowels for a certain length near the surface of the foundation to better distribute the dowel strain into the foundation. Unfortunately, both confining stirrups and debonding of dowels have not been stipulated in Australian design codes. Therefore, future research can evaluate the feasibility and cost-effectiveness of adopting the improved detailing in Australian precast RC walls.

4 Numerical studies of grout tube connections in precast walls

Seifi (2018) proposed a modelling approach for rectangular precast RC walls with grouted dowels by finite element (FE) program VecTor2. However, Seifi (2018) assumed a perfect bond between dowels and grouts, contrary to the experimental observations by Elsayed and Nehdi (2017). Also, the impacts of corrugated ducts on connection behaviour were not considered in Seifi's models, although several studies have demonstrated the importance of the ducts on confining grouts and enhancing connection performance (Elsayed & Nehdi, 2017; Elsayed et al., 2018). Wilson et al. (2008) also numerically assessed the precast RC walls with grout tube wall-foundation connections. They developed two precast wall models subjected to monotonically increasing loads for their experimental specimens. Wall-slab connections with different embedment details were also included in the models. The wall rocking behaviour was simulated by compression-only springs, and connecting dowels were modelled by linear springs. The constitutive laws of the spring elements were adjusted and calibrated against their experimental results. They also performed the push-over analysis to evaluate a full-scale precast wall-frame structure under different soil conditions (Wilson et al., 2008). Therefore, future studies can focus on modelling the hysteresis behaviour of the precast walls and the non-linear time-history analysis of the structure. It is also beneficial to study the appropriate material and bond models that can be utilised by practising engineers in a real-world project for modelling the precast walls with grout tube connections. Additionally, Elsayed et al. (2019) proposed a micro-scale modelling approach for grouted dowel pull-out tests to study the local behaviour of the connection. They used solid elements to model dowels, grouts, and concrete blocks. The interface between dowels and grouts was simulated by cohesive elements in LS-DYNA with a bond stress-slip law derived from Elsayed et al. (2018) pull-out tests. Also, shell elements were selected to model metal ducts. Although Elsayed et al. (2019) reasonably simulated the bond behaviour and ducts, their modelling methodology is too complicated and computationally expensive to be applied in macro-scale models of precast wall buildings.

In the existing literature, the majority of models were developed for grouted dowels in precast bridge columns and bent caps rather than walls. According to Elsayed and Nehdi (2017), the behaviour of grouted dowels in precast walls can be distinct from those used in precast bridge construction, depending on the detailing of dowels and ducts. Hence, directly applying the modelling approach proposed for precast bridges in the simulation of precast walls is unreliable without comprehensive investigation. Also, those models were mainly designed to match specific experimental results but had not been generalised to a level that can be employed for other connections with similar details (Elsayed et al., 2019).

5 Concluding remarks and a plan for future research

The literature review conducted by the authors highlighted the structural behaviour and potential vulnerability of grout tube connections in precast RC walls that have not been previously observed in conventional in-situ RC walls. Current research on the topic is mainly based on laboratory experiments, which are valuable in describing behavioural trends. There is currently limited research based on the numerical modelling of precast RC walls with grout tube connections. Therefore, it is still challenging to predict the behaviour of these precast walls and assess their vulnerability in an earthquake by a cost-efficient approach. In order to bridge the research gaps, the authors will investigate the hysteresis response and seismic behaviour of this type of precast RC walls through computer simulation. The detailing of the walls will reflect the common practice in Australia. The models will consider the bond behaviour of grouted dowels and the confinement effect of corrugated ducts. Finally, the authors will propose a reliable modelling methodology that engineers can follow in a real-world project. A general plan for future research is presented in Figure 5.

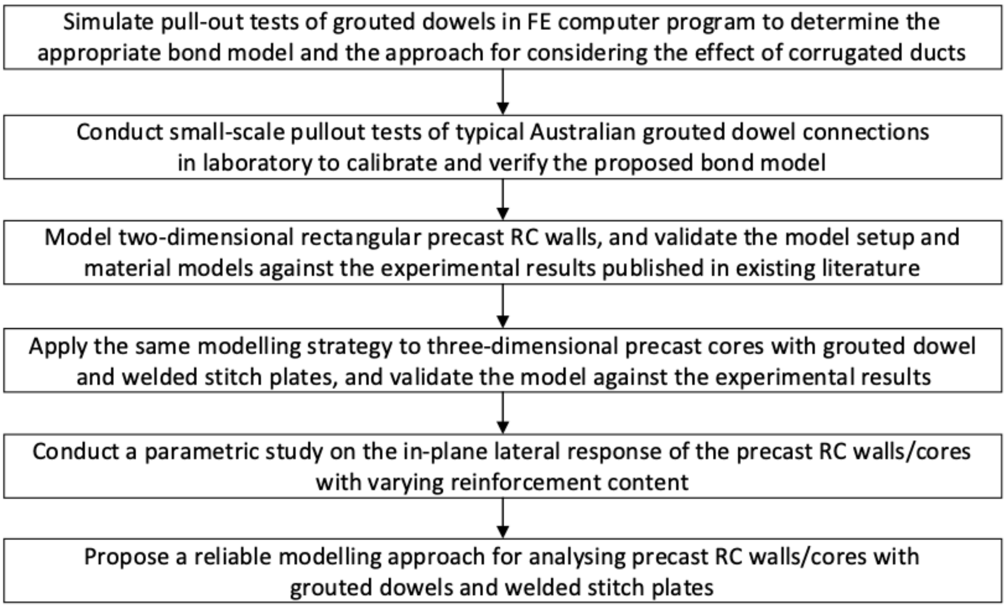


Figure 5. A plan for future research

Note. The flowchart was produced by the authors with the aid of *Microsoft Visio Professional 2019* by Microsoft Corporation, 2019.

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