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A survey focusing on precast reinforced concrete walls in Australia with some preliminary analyses

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Abstract

Previous surveys on Australian precast reinforced concrete walls were mainly conducted before implementing the current version of concrete structure code AS 3600:2018. However, AS 3600:2018 has significant updates on the seismic design and detailing of loadbearing precast walls in buildings. Therefore, the authors recently conducted a new questionnaire survey and a series of interviews with practising engineers to investigate the development status, prevailing design principles as well as detailing practices of precast walls designed per AS 3600:2018. According to the survey responses, the major changes in the design of post-2018 precast walls are the ductility assumption and the reinforcement detailing practices of precast panels and connections. The survey results also show that some practitioners are still confused about the seismic behaviour and load transfer mechanism of grouted dowels and welded stitch plate connections adopted in precast walls. Future research will focus on experimental and numerical investigations of these knowledge gaps.

Keywords: precast RC wall; grouted dowel; welded stitch plate; seismic detailing; survey

1 Introduction

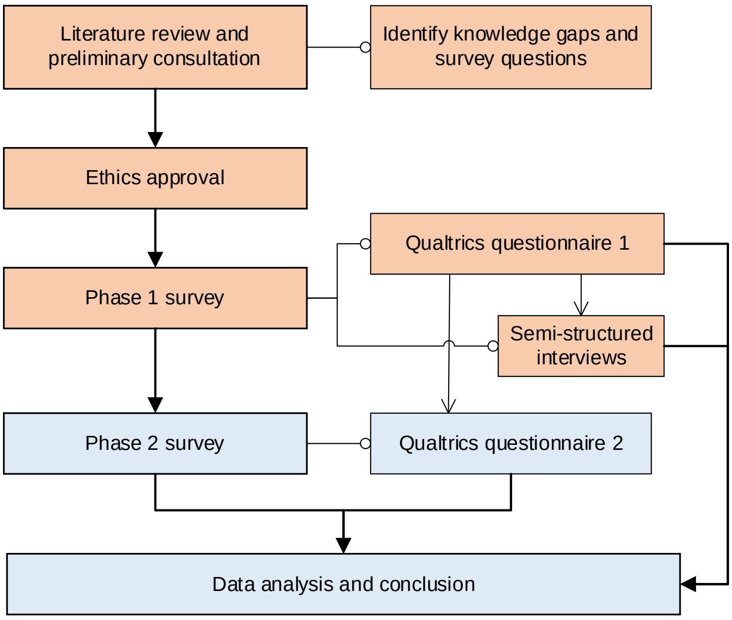
Loadbearing precast reinforced concrete (RC) walls have been utilised in Australian multi-storey buildings for years (Menegon et al., 2017). However, compared to conventional cast-in-place RC walls, practising engineers and engineering students in Australia are still less familiar with the seismic design and behaviour of these precast RC structural walls. An insufficient understanding of the seismic design and detailing practices of precast walls may constrain the development of this structural system.

The Precast Concrete Handbook, published by the National Precast Concrete Association Australia (NPCAA) and the Concrete Institute of Australia (CIA) (2002), is one of the earliest publications that elaborated on the design of Australian precast RC structures. The handbook presents an overview of the design, manufacturing, and installation of various precast RC products, including precast walls. The second edition of the handbook was released in 2009 (NPCAA and CIA, 2009), with changes to accounting for updates of provisions in the concrete structure code AS 3600:2009. However, the handbook has not been updated for the significant changes in the seismic design and detailing of precast walls in AS 3600:2018. Hughes and Crisp (2008) are among the earliest researchers investigating the precast RC walls in Australian multi-storey buildings. They introduced the basic concepts of designing precast RC walls in buildings, which are appropriate for reading by the general public without expertise. Nevertheless, a more in-depth survey about the detailing practices of precast walls is warranted to provide more parameters that can be used by researchers and engineers working in this field. Blismas and Wakefield (2009) conducted interviews and case studies to explore the main benefits and constraints of off-site manufacturing in Australia. However, they mainly focused on the manufacturing and construction perspectives rather than the structural engineering point of view. Menegon et al. (2017) investigated the detailing and construction practices of RC walls in Australian multi-storey buildings, including precast and cast-in-place walls designed per AS 3600:2009. According to their survey of thirty-five residential building cases, precast RC walls were primarily designed for resisting gravity loads. Particularly in buildings incorporating cast-in-place cores and precast RC walls, the lateral loads exerted by wind or seismic actions were sometimes assumed to be fully resisted by cast-in-situ structural cores. In the previous publication by the authors (Weng et al., 2021), the main features and structural behaviour of typical Australian precast structural walls designed per AS 3600:2009 have also been summarised from a thorough literature review. Recently, Navaratnam et al. (2022) surveyed the primary advantages and challenges of developing prefabricated buildings in Australia. They found a growth in the size of the Australian prefabrication industry in recent years. However, considering that there are significant changes in the seismic design and detailing practices of precast structural walls in AS 3600:2018, a more in-depth investigation that specifically focuses on these precast elements is necessary.

This paper presents a preliminary analysis of the survey conducted by the authors on precast RC walls in Australian buildings designed after the implementation of AS 3600:2018. The survey aims to investigate the present 'industry-standard' design and detailing practices of precast walls and their connections (i.e., grouted dowels and welded stitch plates). The survey results are compared with the practices adopted before the release of AS 3600:2018. The authors will use the survey data in designing further experimental and numerical studies on Australian precast RC walls and buildings. The survey outcomes are also expected to help engineering students and the general public better understand these 'new' structural systems.

2 Survey of precast RC walls in Australia

This survey is part of a research project on typical precast RC walls used in low-to-moderate seismicity regions (e.g., Australia). This survey has gained ethics approval from the University of Melbourne (project ID: 23600). Figure 1 illustrates the framework of this survey.



Note: this paper presents the data obtained from the Phase 1 survey

Figure 1. The framework of the survey on Australian precast RC walls

The survey includes two main phases. The first phase intends to investigate the industry-standard practices of designing and detailing precast RC walls and connections. Hence, the focus group in Phase 1 is structural or civil engineers familiar with the structural design of precast RC walls in Australian buildings. Phase 1 of the survey was conducted in August and September 2022 via the online questionnaire platform, Qualtrics (2022). After collecting the data from Qualtrics, the authors interviewed some voluntary participants to gain more insights into the structural design and analysis of these precast walls. This paper presents a preliminary analysis of the valid responses received in Phase 1. Phase 2 of the survey will be conducted in the coming months, which aims to further investigate the main challenges and constraints of applying and promoting precast RC structural walls in Australia. The survey questions will be designed by modifying the questionnaire from Phase 1. It is envisaged that architects, building developers, precasters and builders can be recruited and involved in the survey.

3 Current status of precast RC walls in Australia

The Qualtrics questionnaire of Phase 1 comprises four groups of general questions about the development status, general design concepts and detailing of precast walls and connections. Most of the questions are qualitative and close-ended, including single or multiple-choice questions. A summary of the obtained data is presented in the following sections. The complete Qualtrics survey is available from the authors upon reasonable request.

The questionnaire was distributed to practising structural engineers in major engineering consulting or building design firms in Australia. Eleven valid responses were collected across the country. All the respondents have experience in designing loadbearing precast RC walls in Australia, as shown in Figure 2. Most of these precast wall projects are in Victoria, with some projects based in New South Wales, Queensland, and South Australia. Considering that the survey questions are mainly qualitative and that the applications of precast structural walls in Australia are still relatively limited compared to cast-in-place RC walls, the information obtained from the eleven responses is sufficient and persuasive to achieve the aims of this survey.

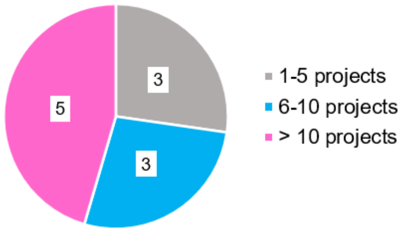


Figure 2. Number of precast wall projects that participants have been involved in Australia

According to the survey results, precast RC walls have been widely used in Australia for loadbearing and non-loadbearing purposes. The loadbearing walls refer to precast walls designed as loadbearing claddings in warehouses and gravity-load-resisting or primary lateral-load-resisting elements in buildings. The non-loadbearing walls include precast walls designed as building façades or internal partitions. The application of precast walls can be found across various building categories, ranging from parking structures and single-storey industrial buildings (e.g., warehouses) to large-scale public buildings and high-rise residential or office buildings. However, it is still relatively rare to employ precast RC walls in Australian domestic houses and small building projects mainly because of the preferences for other construction materials (e.g., steel and timber) and the limited lifting capacity of cranes used in these small-scale projects, as reported by the respondents.

From the survey responses, the current prevailing types of precast wall structural systems include solid precast RC panels spread in multiple locations in buildings and jointed precast RC cores formed by connecting individual solid panels by wet or dry joints. These wall types are similar to those discussed by Menegon et al. (2017) in pre-2018 precast wall construction. Solid precast panels are also used as façades and partitions in various structures. Despite being less common, one respondent reported that pre-tensioned hollow-core precast walls had been used as cladding in some industrial and commercial buildings due to their lightweight and acceptable structural, acoustic, and thermal insulation performance.

Theoretically, precast construction has no specific height limit since loadbearing precast walls are designed and detailed to achieve an equivalent structural performance to cast-in-place RC walls. However, if the lateral loading is excessive, the on-site construction of connections in precast walls could be complicated and costly, thus compromising the benefits of using precast walls. According to the survey, if precast walls are used for loadbearing purposes in medium-to-high-rise buildings, the maximum preferential number of storeys is approximately 15 to 20 storeys, depending on the degree of loading acting on the walls.

4 Benefits and constraints of using precast RC walls in Australia

Researchers often praised precast RC construction for improved durability, faster construction speed and reduced waste and pollution (Navaratnam et al., 2022; NPCAA & CIA, 2009; Polat, 2008; Yee, 2001). Although loadbearing precast RC walls have been internationally studied and promoted for some decades (Priestley, 1991), only recently have these structural walls become popular in Australian multi-storey buildings (Menegon et al., 2017). Therefore, it is critical to understand practitioners' options regarding the main factors affecting the development and promotion of precast RC structural walls in Australia. The outcomes could assist researchers in determining the future research direction.

Two questions in the Phase 1 questionnaire asked practising engineers' opinions about the benefits and challenges of adopting precast RC walls in Australia. The participants were required to score a list of advantages (Table 1) and constraints (Table 2), ranging from 0 (not at all) to 5 (entirely). The factors in the tables are proposed based on the authors' experience, preliminary consultations with practitioners and a review of surveys conducted internationally on precast construction (Blismas & Wakefield, 2009; Hughes & Crisp, 2008; Jaillon & Poon, 2010; Jiang et al., 2018; Li et al., 2018; Liu & Zhang, 2020; Navaratnam et al., 2022; Polat, 2008; Xue et al., 2017). In addition to the factors predefined by the authors, the participants are allowed to enter their own answers via Qualtrics. Tables 1 and 2 also present the arithmetic mean of the scores from the eleven participants for each factor. The sample standard deviation is calculated by using Equation 1. Due to the limited number of respondents in this phase, the data shown in the tables may not have sufficient statistical power to draw a fully solid conclusion. However, understanding practitioners' opinion about the predefined factors helps the authors design the questionnaire for Phase 2 of the survey, in which more participants from different sectors (e.g., architects, building developers, precasters and builders) in the building industry will be recruited. The benefits and constraints supplemented by some respondents in the Phase 1 questionnaire will be added to the Phase 2 questionnaire.

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad (1)$$

Table 1. Participants' responses to the benefits of using precast RC walls in Australia.

Rank	Factors	Mean score	Standard Deviation
1	Reduced overall construction time	3.64	1.43
2	Reduced on-site work and associated labour costs	3.45	1.21
3	Reduced overall project costs	3.00	1.34
4	Reduced pollution and/or waste	2.80	1.75
5	Aesthetics / better product quality	2.55	1.44
6	Favourable policies and/or regulations	2.50	1.35
7	Better structural performance (Compared to cast-in-situ RC walls)	1.45	1.29

Table 2. Participants' responses to the constraints of using precast RC walls in Australia.

Rank	Factors	Mean score	Standard Deviation
1	Uncertainty about the structural performance of precast RC walls	2.55	1.69
2	Complex structural design and detailing	2.27	1.35
2	Difficult/poor on-site construction operations/installation	2.27	1.35
3	Complex project management/planning	2.27	1.56
4	Difficulty in applying BIM or other Information and Communication Technologies	2.00	1.61
5	Complex architectural design	1.91	1.38
6	Transportation issues	1.91	1.64
7	Lack of supply chain/manufacturers of precast RC walls	1.36	1.57
8	Public's concerns about the safety of precast RC walls	1.09	1.30
9	Increased initial investment	1.09	1.38
10	Lack of expertise in the industry	1.00	1.34
11	Unfavourable policies and/or unclear regulations	0.60	0.97

Note: If two factors have the same mean score, the one with a smaller sample standard deviation is given a higher rank.

Survey results show that among the predefined benefits listed in Table 1, the leading advantages of employing precast RC walls in Australia are reduced on-site work, construction time, and associated labour costs. However, one anonymous respondent commented that if the number of wet joints in precast walls is extensive, these benefits will be negated. Therefore, the contractors sometimes prefer using dry joints (e.g., welded stitch plates) as the vertical connections between precast walls. The least recognised benefit is the 'better structural performance'. Although intuitively, cast-in-place RC walls have superior or at least equivalent structural performance compared to precast RC walls, recent research has proven that innovative precast wall systems using energy dissipation and self-centring devices can achieve better seismic performance than monolithic cast-in-place walls, particularly in terms of displacement capacity and ductility (Li et al., 2020; Wu et al., 2022). These innovative features have not been incorporated into loadbearing precast walls in Australia, probably because it is not economically feasible to employ energy dissipation devices in a low-to-moderate seismicity region. Apart from the benefits predefined by the authors in Table 1, two respondents added that precast walls also have advantages in pre-applying architectural finishes in the factory and eliminating the difficulty of compacting concrete on the project site.

According to the responses, the greatest barrier to applying precast RC walls is the uncertainty about their structural performance, followed by complex structural design and poor on-site work. This ranking is somewhat predictable because the respondents are structural or civil engineers who may have more concerns about structural design and detailing than the average engineers. Hence, recruiting more participants from diverse sectors in the next phase is critical to generalise the survey results. It is worth mentioning that a large standard deviation of 1.69 for the 'uncertainty about the structural performance' factor indicates a great variance in the obtained responses. The authors will re-interview some of the respondents who gave a low score for the 'uncertainty' factory (meaning that they are more confident with the structural performance of precast walls) to understand how they perceive structural performance, for instance, whether they only check the capacity against code provisions or will conduct analyses to predict the displacement demand. It is noted that some practising engineers stated that if the seismic analysis is carried out based on the normative approaches (i.e., Equivalent Static Analysis and Modal Response Spectrum Method specified in AS1170.4), there is no significant difference in seismic performance between precast and cast-in-place structures. However, when evaluating the two systems by nonlinear push-over analyses (i.e., Capacity

Spectrum Method), the precast system would perform worse than the monolithic structure under earthquake loads. More numerical investigations are needed to consolidate this finding.

From the survey data, the least significant constraints are the lack of expertise and unfavourable policies and regulations. In the 2009 investigation into the benefits and challenges of off-site manufacture in Australia by Blismas and Wakefield (2009), the major constraints of implementing off-site manufacture are lack of skills and expertise in the building industry. Therefore, at least from the perspective of structural engineers, there appears to be more expertise in precast wall design at present than a decade ago. Besides the factors listed in Table 2, one respondent added that the insufficient lifting capacity of cranes limits the use of precast walls in small projects. Interestingly, another respondent pointed out the issue of using low-carbon concrete in precast walls, which makes precast elements less sustainable than their cast-in-place counterparts. Low-carbon concrete with a high fly ash content has been widely used in the Australian building industry mainly for eco-friendly reasons. However, this type of concrete has a reduced early-age strength due to high fly ash content (Sofi et al., 2017). Because sufficient early-age strength is critical for accelerating precast wall installation to reduce construction cycles, the application of low-carbon concrete in the precast industry is limited, which also constrains the applications of precast walls in some projects.

5 Typical detailing and general structural design principles of loadbearing precast RC walls in Australia

The authors have previously reviewed the detailing of precast walls designed per AS 3600:2009, as reported in Weng et al. (2021). Because AS 3600:2018 has some major updates on the seismic design and detailing of structural RC walls (including loadbearing precast walls), the authors conducted a new survey to investigate the recently designed precast RC walls. The survey data are summarised in Table 3 with comparisons to the detailing adopted in precast walls designed per AS 3600:2009.

Table 3. Comparisons of precast walls designed per AS 3600:2018 and AS 3600:2009

<table>
<tr><th colspan="2">Parameters</th><th colspan="3">Precast walls designed per AS 3600:2018</th><th>Walls designed per AS 3600:2009</th></tr>
<tr><td rowspan="4">Dimensions</td><td rowspan="2">Thickness</td><td colspan="2">150 mm</td><td>singly reinforced precast walls</td><td rowspan="5">Similar to walls designed per AS 3600:2018. But for the pre-2018 walls, there is no specific requirement for the wall aspect ratio and effective height-to-thickness ratio.</td></tr>
<tr><td colspan="2">180 mm to 300 mm but can be up to 400mm in some projects</td><td>doubly reinforced precast walls</td></tr>
<tr><td>Height</td><td colspan="3">3 – 6 m</td></tr>
<tr><td>Length</td><td colspan="3">2 - 3.4 m</td></tr>
<tr><td>Concrete</td><td>Grade</td><td colspan="3">N32 (less common), N40 (the most common) or N50</td></tr>
<tr><td rowspan="3">Reinforcement</td><td>Vertical</td><td colspan="3" rowspan="3">See discussion below</td><td rowspan="2">Single layer or two layers of L-grade mesh with additional N-grade trimmer bars at wall ends</td></tr>
<tr><td>Horizontal</td></tr>
<tr><td>Ligature or ties</td><td>N/A</td></tr>
<tr><td rowspan="4">Connections</td><td rowspan="2">Horizontal connections</td><td rowspan="2">Grouted N-grade dowels in spiral metal ducts</td><td colspan="2">N20 dowel = 50mm diameter duct
N24 dowel = 60mm diameter duct
N28 dowel = 70mm diameter duct</td><td rowspan="4">In general, the connections used in pre-2018 precast walls are similar to walls designed per AS 3600:2018. But AS 3600:2018 stipulates stricter requirements for the design and detailing of grouted dowels, as discussed below.</td></tr>
<tr><td colspan="2">Grout strength varies from 50-80 MPa but is typically one grade higher than the wall concrete</td></tr>
<tr><td>Vertical connections</td><td colspan="3">Wet joints or welded stitch plates (more common)</td></tr>
<tr><td>Wall-to-slab connections</td><td colspan="3">cast-in ferrules, concrete corbel, steel shelf angles</td></tr>
</table>

From the survey responses, the reinforcement detailing of recently designed precast walls varies depending on the preference of design offices and the functions of the walls. For gravity-load-resisting or non-loadbearing purposes, the precast panels are typically reinforced with one or two layers of low-ductile mesh with additional normal-ductile vertical perimeter rebars at wall ends, similar to pre-2018 precast walls (Menegon et al., 2017). A single layer of D500N bars is also used in some gravity-load-resisting walls, but it is much less common. For precast walls designed as primary lateral-load-resisting elements, it is now common to reinforce the panels with two layers of N-grade bars, although some respondents reported that they would still prefer to use low-ductile mesh in precast walls subjected to lateral loads. The 'gravity-load-resisting walls' mentioned here are somewhat misleading. One respondent commented that there is no such thing as 'gravity-load-resisting only walls' because once precast walls are tied to floor diaphragms, a non-negligible degree of lateral loads will be distributed to the walls depending on their lateral stiffness. Hence, precast structural walls should always be designed for lateral-load-induced drifts and design actions, like the columns in gravity frames. At least according to the received survey responses, newly designed loadbearing precast walls are always checked for seismic and wind loads. One engineer further noted that even if the walls are employed as loadbearing cladding, they will consider the effect of earthquake and wind actions by checking the out-of-plane bending. Because AS 3600:2018 stipulates stringent confinement requirements for boundary elements and plastic hinge regions of limited-ductile walls, the respondents also highlight the need for providing stirrups and 'U' bars at wall ends and 135º hooks for horizontal lapped bars in newly designed precast walls.

As found in the survey, L-grade mesh is still used in the precast industry. However, previous experimental tests have demonstrated that precast walls with low-ductile mesh are prone to brittle bar fracturing failure (Menegon et al., 2019a, 2020a). The low-ductile steel has a low strain hardening ratio and small ultimate strain, which would also constrain the distribution of cracks and the development of displacement ductility in precast walls (Standards Australia, 2022; Menegon et al., 2019a). Even if precast walls are reinforced with two layers of low-ductile mesh, the elements may still exhibit an undesired and unpredictable cracking pattern under lateral loads (i.e., a concentration of cracking at a random location) (Menegon et al., 2019a). Providing two additional N-grade perimeter bars at the wall edge might not improve the structural performance as expected. It is because the low-ductile steel could still be fractured significantly earlier than normal-ductile steel bars under strong ground motions, forming a weak point and impairing the wall integrity and robustness (Menegon et al., 2020a). In addition, if only one layer of reinforcement (whether class L or class N) is placed in precast walls, the elements will become sensitive to out-of-plane loads and disturbance, which might cause out-of-plane instabilities and bar buckling (Menegon et al., 2019a). Regarding the ductility assumption adopted in the seismic analysis, all the respondents reported that if L-grade mesh or a single grid of reinforcement is used in lateral-load-resisting precast walls, they will now analyse the elements as non-ductile walls per AS 3600:2018. According to one respondent, the pre-2018 precast wall reinforced by L-grade mesh was previously and incorrectly designed for a ductility factor of 3. It seems like this misconception has been eliminated.

Grouted dowels are still the most common type of horizontal connection in Australia. According to the survey, constructability and the availability of materials in the local market are the controlling factors for determining the kind of connection used in precast walls. The material properties of grouted dowels are generally similar to those adopted in precast walls designed per AS 3600:2009. However, AS 3600:2018 stipulates more onerous requirements for the design and detailing of grouted dowels. For limited-ductile precast walls, the connection dowel reinforcement ratio now requires to be greater than the wall vertical reinforcement ratio. For non-ductile precast walls, the dowel reinforcement ratio shall exceed 50% of the wall vertical reinforcement ratio (Standards Australia, 2021). Furthermore, according to the survey responses, the development length of dowels is typically calculated following the same approach used for conventional RC walls but may conservatively be assumed as non-contact lap splices. This equivalent design assumption might be considered acceptable in the absence of a design equation specially developed for grouted dowels. However, more experimental tests are needed to better understand the local load-transfer behaviour of these connections. Alternatively, as per AS 3600 Sup 1 C17.7.5 (Standards Australia, 2022), engineers can evaluate the load transfer between dowels and wall vertical reinforcement by a strut-and-tie method. According to the survey responses, practitioners will also refer to American code ACI 318 and ASCE 7 and various industry design guidelines, such as the 'Precast Concrete Handbook' by NPCAA and CIA (2009) and the grouted precast joints guideline by NPCAA (2020), for the design of precast walls and grouted dowels.

The most common type of vertical connection between precast panels is still welded stitch plates, as reported by the respondents. The design of jointed precast systems with these dry connections is much more complicated than that of individual precast walls. Previous earthquakes and experimental testing have found that dry connections are often the critical elements in precast structural walls subject to seismic loads because these connections are typically the most flexible components in the wall system and attract more deformations (American Concrete Institute, 2013; Menegon et al., 2020b). Hence, the dry connections should be designed with sufficient strength and stiffness to effectively transfer the loads acting on the precast systems. In general, the design of welded stitch plates will follow the relevant provisions in AS 4100, AS 5216 and AS 2327. Special attention should be paid to the global structural modelling of precast walls or cores with welded stitch plates. Per the survey responses, edge shear forces between individual precast panels can be partially released to account for the loss of shear rigidity due to the flexibility of welded stitch plates. It should be noted that releasing the wall edge shear may significantly change the distribution of rigidity in the structure and alter the dynamic response of the building. However, there is no well-known guidance for defining the edge shear force releases in the analysis of composite precast walls or cores with welded stitch plates. Further experimental and numerical investigation on these dry connections and jointed precast core systems is necessary. As an alternative modelling approach, the AEFAC technical note (AEFAC & Swinburne University of Technology, 2022) recommends that welded stitch plates can be modelled as discrete line elements with stiffness estimated following the approach proposed by Menegon et al. (2020b).

6 Concluding remarks

Previous reviews and surveys on Australian precast walls' features and detailing practices are mainly based on the walls designed per the 2009 edition of AS 3600. However, the design of loadbearing precast RC walls has been significantly updated after the implementation of AS 3600:2018. Therefore, the authors recently surveyed the newly designed (post-2018) precast RC walls in Australian buildings. This paper presents a preliminary analysis of the valid survey data provided by eleven practising engineers. According to the survey responses, the main differences between loadbearing precast walls designed per AS 3600:2009 and AS 3600:2018 are the changes in the ductility assumption and the reinforcement detailing of precast panels at boundary elements, plastic hinge regions and grouted dowel connections. The more stringent structural design requirement particularly aims to improve the ductility and integrity of precast RC walls.

Furthermore, this paper discusses the current design practices of welded stitch plates used in precast walls from interviews with practising engineers. However, further investigation is needed to assess the behaviour of welded stitch plates with different shear stud configurations and the system-level ductility of buildings supported by precast walls with these dry connections. In the next phase, the survey data will be used to design the experimental specimens and numerical models for evaluating the seismic performance and potential vulnerability of this precast system.

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