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Self-Aligning Structural Connection for Precast Concrete Wall Panels

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Abstract: Due to the rise in modular construction in recent years, precast concrete construction has become increasingly common and as a result there has been a focus on improving the process. It has become popular as it can reduce construction times, be higher quality, and be more cost effective for large-scale projects; however, the industry has identified the lack of available connections for precast elements as a significant area for improvement, as well as the overall efficiency of the construction process. To address these issues, a bolted connection for use in total precast construction projects between wall panels was designed. The new connection is self-aligning and aims to reduce the accumulation of tolerance errors that can occur in precast construction. To do this, the connection uses a perforated steel frame within the wall panels that u-shaped inserts are bolted to. The frame is responsible for maintaining squareness and alignment rather than the surrounding concrete and the improved accuracy may allow for mechanical, electrical, and plumbing components to be installed in the wall framing in the plant and further reduce on-site construction times. For the horizontal connection between adjacent wall panels, a z-plate is used between u-shaped inserts, while for the vertical connections that span across floor slabs, a long flat bar connects the u-shaped inserts. This examined the fit of the connections and tested this by assembling three concrete wall panels, two lower panels and one upper panel, to assess the constructability of both the connection types.

Keywords: Precast concrete; concrete walls; structural connections

1 INTRODUCTION

Modular construction has seen a significant rise in use in recent years. The current trend in the construction industry is to move away from traditional construction methods towards modular construction (Rossley, et al. 2014). Modular construction is the process of fabricating the elements in a factory and shipping them to site for assembly. It's most commonly applied in low-rise construction projects that are able to use repeating units, such as apartment buildings or office, to maximize efficiency (Thai, Ngo and Uy 2020).

The shift towards modular construction has been for several reasons. Most notably, its ability to significantly reduce on site construction times (Lawson, Ogden and Bergin 2012). Another advantage is that modular construction reduces the on-site labour requirements during construction and can reduce the number of labourers required overall (Ferdous, et al. 2019). Fewer labourers are typically necessary to complete the same task in a factory compared to on site (Molavi and Barral 2016). The combination of reduced labour and the overall quicker construction time also often reduces the costs of the project. This is particularly true for larger-scale projects (Lawson, Ogden and Bergin 2012). Modular construction has also been shown to improve safety for workers and improve the quality of the end product (S. Singhal, et al. 2019). The ability to manufacture the elements in a controlled environment ensures meeting a higher standard for quality

(Priya and Neamitha 2018). Modular construction has a lower impact to the public in terms of traffic and noise (Kalasapudi, et al. 2015).

Precast concrete construction is one of the common methods in modular construction. The lack of available connections that are able to be used in precast concrete construction projects has been identified as a limitation on this industry (Vaghei, et al. 2017). Therefore, a new self-aligning connection was designed for this specific use. The connection is being assessed for constructability and fit as well as being compared to traditional methods of connecting precast concrete wall panels.

2 LITERATURE REVIEW

2.1 Wall Panel Connections

Total precast concrete construction refers to the practice of building a structure entirely from precast concrete elements. One type of total precast system is referred to as a wall frame structure, which combines floor slabs and load-bearing wall panels (Rossley, et al. 2014). In designing precast concrete structures, the connections are integral to ensuring loads are properly transferred between the different elements. The proper transfer of lateral loads is particularly important in seismic applications (Vaghei, et al. 2017). They also must meet requirements for strength, ductility, and rigidity, which greatly impact the overall capacity and stability of the structure (Rajanayagam, et al. 2021).

Connections for precast concrete are categorized as either wet or dry. Wet joints, or wet connections, connecting two precast elements, are those that rely on pouring additional concrete or grout on site to complete the connection. A typical type of wet joint is grout sleeve connections which use rebar extending from one element that matches up with empty sleeves on the adjacent element. Once the rebar is in place, the sleeves are filled with grout which allows the connection to imitate the monolithic behaviour that occurs in cast-in-place construction (Cheng, Cai and Looi 2021). In precast concrete construction using the wall frame system, this type of connection is typically between lower and upper wall panels where they join and create a vertical joint. Another type of wet joint often used between wall panels is the loop bar or loop wire connector. This connection uses u-bars or looped steel wire protruding from adjacent wall panels with a reinforcing bar placed through the loops. The gap is then filled with in-situ concrete (Singhal, Chourasia and Kajale 2022). Dry connections are common and are either welded or bolted connections which are completed on site (Vaghei, et al. 2017). Dry connections are favourable due to their faster assembly on-site compared to wet joints (Cheng, Cai and Looi 2021).

Connections used in precast construction must meet certain standards and requirements and the lack of available connections that accomplish this has been identified as an impediment to making progress in this industry (Vaghei, et al. 2017). The connections should be easy to assemble, reduce construction time, and lower the costs (Cheng, Cai and Looi 2021). It is also advantageous that they can be disassembled (Rajanayagam, et al. 2021).

2.2 Tolerances

Tolerances are allowable variations from the values specified by the design. These include product tolerances which govern the amount of variation that a dimension of an element can have and erection tolerances which are deviations in the placement of a component (Precast/Prestressed Concrete Institute 2010). Tolerance errors are highly prevalent in all modular constructions including precast concrete construction. They have significant negative impacts on a project, including producing structural inadequacies, delaying construction, increasing overall on-site time, increasing costs, and increasing material waste (Talebi, et al. 2021). The Precast/Prestressed Concrete Institute (PCI) recommends, for example, that variations in length for structural wall panels be kept +/- ½ in. (12.7 mm), while the variations in width and depth are kept at +/- ¼ in. (6.35 mm) (2010).

Tolerance errors are most often caused because of variations in manufacturing the precast components and the effects have to be addressed on site, often requiring significant work (Talebi, et al. 2021). The low tolerance requirements and capacity in precast construction have been found to allow for the accumulation of tolerance errors to occur over the whole structure (Kalasapudi, et al. 2015). Tolerance errors often impede the ability to connect elements together, while there is a notable lack of connections in precast construction that can address tolerance errors. For instance, the grout sleeve connections often fail to meet tolerance requirements, causing the rebar to not properly align with the sleeve and require adjustment on-site.

3 CONNECTION CONCEPT AND DETAILS

To address the potential for the accumulation of tolerance errors in precast concrete construction, a new self-aligning bolted connection was designed for precast concrete wall panels. The connection is intended for use in total precast concrete construction projects, where the building is formed by a combination of precast concrete wall panels and precast concrete floor slabs. The connection would reduce the effect of tolerance errors on the structure by using an internal frame in the precast wall panel and bolting into u-shaped connections which accommodate adjustment on-site. The internal frame can meet stricter tolerance requirements compared to the concrete itself. The connection components are then bolted to the frame. The increased accuracy of the wall panels may also allow for mechanical, electrical, and plumbing (MEP) elements to be installed directly in the wall panels during fabrication in the plant and further reduce the number of processes that occur onsite. The overall concept of the precast wall panel with the internal frame, connections, and the potential MEP route is shown in Figure 1.

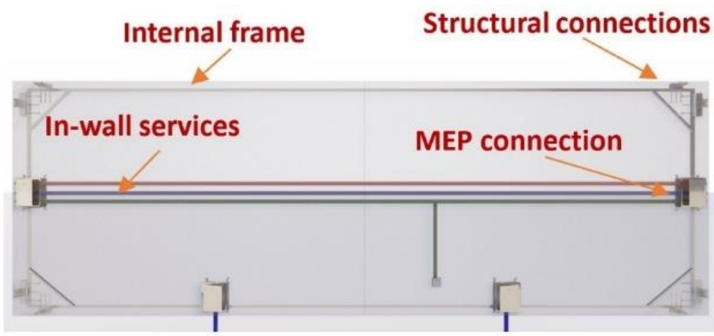
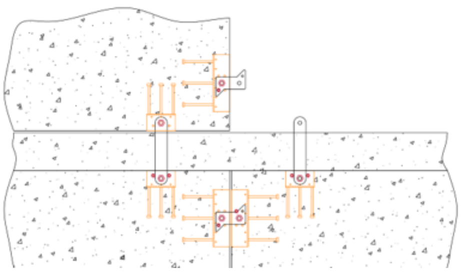
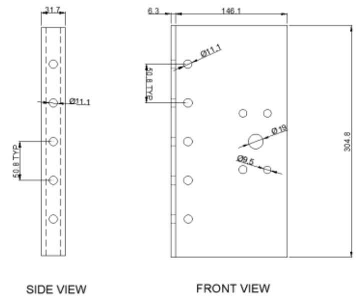


Figure 1: Connection Concept

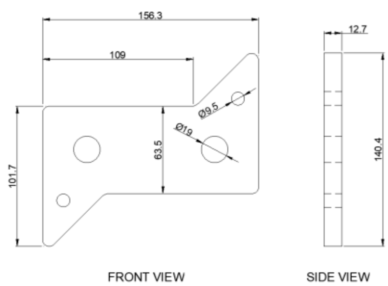
The connection components are of two types: horizontal and vertical. The connection components are in Figure 2 as well as the overall connection details. The horizontal connections are located between adjacent wall panels and the vertical connections span between upper and lower wall panels through floor slabs. This is shown in Figure 2a. Both types of connections rely on a u-shaped insert shown in Figure 2b. To form the u-shaped insert, two vertical and one horizontal plate are welded together. At the horizontal connections the u-shaped inserts on adjacent wall panels are connected via a z-shaped steel plate, shown in Figure 2c, referred to as a z-plate. At the vertical connection, a flat bar connector, Figure 2d, is used between the u-shaped inserts. The connections use a combination of structural and alignment bolts. Each u-shaped insert has one structural connection point, which uses a ¾ in (19.05 mm) shoulder bolt and connects to either end of a z-plate or a flat bar. A pattern of four 3/8 in (9.53 mm) secondary alignment bolt holes is around the main bolt hole on the u-shaped inserts. These bolts are used in the self-aligning process and to prevent excessive rotation or movement of the z-plate or the flat bars during the connection.



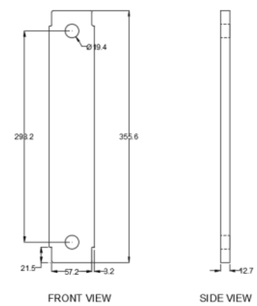
(a) Elevation view of connection system including wall-to-wall and wall-through-floor



(b) U-shaped insert



(c) Z-plate



(d) Flat bar connector

Figure 2: Connection details

To form the connection, the z-plate is inserted into the u-shaped insert of one wall panel and secured with both a structural bolt and the alignment bolts to prevent movement of the z-plate, and then an alignment bolt is placed in the connecting u-shaped insert. As the wall panel is moving into place, this alignment bolt guides the wall panel into place, and then gets secured with a structural bolt to complete the connection. The flat bar connector is fitted into the u-shaped inserts of the lower panel and secured with a structural bolt. Two alignment bolts are also placed in the u-shaped insert to prevent unrestrained rotation, but still allow for some movement needed to smoothly place the wall panel. The connections have been tested for capacity under in-plane tensile loading. Depending on the detailing and configuration of the connection, capacity was found to be in the range of approximately 200 kN to 400 kN.

4 RESEARCH METHODOLOGY

4.1 Research Design

To assess the ability of the connection to address tolerance errors in construction as well as the constructability and overall fit of the connection, reinforced concrete wall panels were built with the internal frame and connections embedded. The connection components, including the u-shaped inserts, z-plates, and flat bar connectors, had been laser cut to the specified dimensions to ensure accuracy. Three wall panels were then assembled with two lower panels and one upper panel to evaluate both the horizontal and vertical connection types. The assessment of the assembly process of the wall panels was also used to compare to traditional methods of wall-to-wall connections in precast concrete construction. For the purposes of this research, the connections were compared to grout sleeve connections, which are common in precast concrete construction, particularly in total precast projects. The comparison aims to consider the ability of the connections to address tolerance errors and to improve efficiency, while also noting any deviations from typical processes. Cost comparison of the connections was outside the scope of this paper.

4.2 Data Collection and Analysis

Information on the process for the use of the grout sleeve connections was provided by an industry partner and through observing both on site and in the plant construction projects engaging this method. The comparison was made with the new self-aligning connection using a table comparing the steps in the two processes. To assess the connection for constructability and fit, wall panels were constructed with the connection components. Evaluations of the process were done during both the construction phases of the wall panels and during assembly of the wall panels to determine areas for improvement. This process was used in the comparison with a typical connection while also considering any deviations that would be expected if this were to be used in a full-scale construction project.

4.2.1 Wall Panel Construction

Four 2 m x 2 m x 200 mm reinforced concrete wall panels were constructed. To build the concrete wall panels, internal frame for each panel was constructed from 1.75 in. (44.45 mm) square perforated steel tubing that had 7/16 in. (11.11 mm) diameter holes with 1 in. (25.4 mm) centre-centre spacing. The frames were built such that the edges of the u-shaped inserts would be at the edges of the wall panels. The four edges of each frame were connected using L-shaped brackets at the corners and braces made from the same perforated steel tubing material and located at the corners and connected to the main frame using Y-shaped brackets. The frame is shown in Figure 3a. Each internal frame had eight connection locations, two per side. The u-shaped inserts were bolted to the frame at these locations as shown in Figure 3b.

The bolt holes need to be protected from being filled by concrete during casting of the concrete. For the connections to be functional after casting, the space for the bolts must be present in the wall panels. To ensure this, the wall panels were cast with the structural bolt and four alignment bolts in place at each u-shaped insert. However, the bolts had to be removable post casting to allow for the connection. This was achieved using PVC conduits. The conduits protected the bolts which were tightened into cap nuts, thus preventing concrete from making contact with the bolts during casting. The openings of the PVC conduits were also covered with duct tape or filled with paper towel to prevent concrete from filling that area during casting. Additionally, the u-shaped inserts were filled with Styrofoam to protect them from getting filled with concrete.

(a) Internal frame

(b) Attachment of u-shaped inserts

(c) Protective conduits for bolts during casting

Figure 3: Details of internal frame and u-shaped inserts during construction

The wall panels were all designed to have one layer of reinforcement mesh, with 1960 mm long 10M reinforcing bars spaced at 196 mm off-centre in both directions. Timber form works were built to cast the wall panels. The frames were lifted and placed into the forms using a crane and then the rebar meshes were placed on top and adjusted as necessary to prevent interference between the reinforcement and the connections on the steel frame. Concrete was then poured and vibrated to ensure proper consolidation. After the 28 days of required curing time for the concrete, the forms were stripped from the wall panels. The bolts were removed from the PVC conduits, and the portions of the conduits that extended from the wall panels were cut flush with the face of the wall panel. The Styrofoam was also removed from the u-shaped inserts.

4.2.2 Wall Panel Assembly Process

Three concrete wall panels with the self-aligning connection system were assembled in lab. The process for assembling the wall panels in the lab is shown in Figure 4. To assemble the wall panels, a bracing system was built to support the lower wall panels on the floor vertically. The braces were made of W and channel steel sections. The first wall panel was lifted and placed into position and then the braces were adjusted to secure it. The lower wall panels were shimmed. Before placing the second lower wall panel, z-plates were placed in the two u-shaped inserts of the first panel that would be used in forming the horizontal connection between the panels. The z-plates were each secured with main structural bolts and then an alignment bolt was placed for each one to ensure they remained level. Alignment bolts were also placed in the u-shaped inserts of the second wall panel. The second wall panel was then lifted and placed into position. The crane and the alignment bolts guided the panel into place. The connection of the two walls was completed with structural bolts placed in the second wall panel attaching the two components.

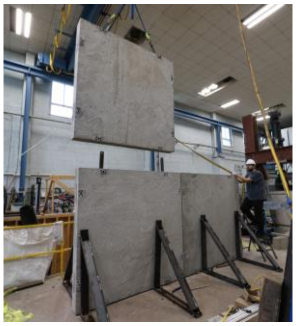
Flat bar connectors were attached to the u-shaped inserts along the top of one of the lower wall panels. The flat bars were connected with the main structural bolt and then two alignment bolts were inserted to prevent excessive rotation of the flat bars. The upper wall panel was lifted using a crane and guided into place. Once the wall panel was lowered into place, the connection was secured at the upper panel with the main structural bolt. The upper panel remained supported by the crane through the assembly process.

(a) Placement of first wall panel

(b) Placement of second wall panel

(c) Placement of second wall panel

(d) Final horizontal connection



(e) Placement of upper panel

(f) Final assembly of wall panels

Figure 4: Assembly of wall panels

5 RESULTS AND ANALYSIS

5.1 Comparison of Connection Processes

To compare the process of installing wall panels with the self-aligning connection versus the typical grout sleeve connections, a comparison table was created showing the steps both in the plant and onsite. Table 1 summarizes the steps needed to assemble a typical wall panel for each connection type. It was found that the number of principal steps required for the erection of a wall panel with the self-aligning connection is fewer, 11 steps, compared to a typical grout sleeve connection, 12 steps. This is true particularly for the onsite steps in the process where the use of the self-aligning connection can eliminate the need for onsite adjustments to the connection to ensure a good fit as well as levelling and shimming, which can be labour and time intensive. For the self-aligning connection, the mentioned steps are anticipated if it were to be used in a precast concrete construction project and is based on the construction and assembly that occurred in the lab.

Table 1: Comparison of on-site and off-site processes for self-aligning connection and grout sleeve connection

Off-Site process for self-aligning connection	Off-Site process for grout sleeve connection
1. Fabricate internal frame and install connection components	1. Lay rebar, grout sleeves, rebar couplers, horizontal connections and lifting connections and pour concrete
2. Lay rebar and frame and pour concrete	2. Cure for 24-48 hours
3. Cure for 24-48 hours	3. Strip forms and store for remainder of curing time (28 days)
4. Strip forms and store wall panel for remainder of curing time (28 days)	4. Transport to construction site
5. Transport to construction site	

On-Site process for self-aligning connection	On-Site process for grout sleeve connection
1. Install z-plates and flat bar connectors in wall panel	1. Lift wall panel into place with crane
2. Lift wall panel with crane and place using self-aligning mechanism	2. Adjust extending reinforcement from other wall panels as necessary to ensure alignment with corresponding grout sleeves
3. Secure with bolts on connecting wall panel	3. Lower wall panel into place
4. Install bracing	4. Level and shim wall panel
5. Grout joints	5. Fill sleeves from connecting panel with grout
6. Repeat for subsequent wall panels	6. Install bracing
	7. Grout/fill vertical space between adjacent wall panels
	8. Repeat for subsequent wall panels

Regarding the issue of tolerance errors in precast concrete construction, the new self-aligning connection improves accuracy compared to typical connection methods for precast concrete wall panels. The use of the internal frame ensures that the connections are made with a higher degree of accuracy and maintains a higher degree of consistency across the entire structure. Other methods require significant levelling and shimming for each element that is installed and are heavily affected by the low accuracy of the concrete wall panels themselves. The tolerances of the holes in the self-aligning connection were specified to be laser cut to 1/64 in. (0.4mm) oversized diameter. This can be compared with traditional steel bolted connections that work with 1/16 in. (1.59mm) oversized diameter. Precision of concrete wall panel edges are controlled by the manufacturer and may be up to ¼ in. (6.35mm) off due to incorrect placement of forms and bowing of formboard during casting. Levelling and shimming for wall panels with the self-aligning connection is not needed as the connection is frame to frame and more accurate. While some shimming of the wall panels was done during assembly in the lab, this is not typically a necessary step as the connection points along the bottom of the lower wall panels are also able to be used and would connect into an element that is already levelled at the bottom storey.

Connections such as grout sleeves require grout to drying order to achieve their structural capacity. They also require significant bracing to be installed during assembly. While bracing may be required for the current self-aligning connection, it is likely that it will be require less quantity and duration. The reason is that the self-aligning connections achieve their structural capacity immediately after placement and do not require hardening of grout to be able to transfer loads between the elements. When using self-aligning connections, the joints between the wall panels will be grout filled, but the connection itself will be responsible for the structural integrity. The use of traditional connection methods also requires the installation of lifting points in the wall panels. This requires additional labour in the plant. For the self-aligning connection, the u-shaped inserts along the top of the wall panel can serve as lifting points and thus reduce the need for additional labour and time.

5.2 Assessment of Self-Aligning Connection

The proposed self-aligning connection requires some improvement to refine the connection. First is that the tolerance on the bolt holes in the z-plate should be tightened. When designing the connection components, a tolerance of 1/64 in. (0.40 mm) was added to the diameter of the bolt holes to ensure that the connection could be made. However, this ended up allowing too much rotation of the z-plates. They were able to rotate slightly around the structural bolt as the alignment bolt did not hold it perfectly secure. This impeded the ability to form the horizontal connection during assembly but did not have a noticeable impact on the vertical connections.

During the construction phase of the wall panels, it is also imperative that care is taken not to overtighten the bolts when placing them in the u-shaped inserts prior to casting. While it is important to tighten the bolts adequately such that no concrete can penetrate the PVC conduits, overtightening the bolts deformed the u-shaped inserts and reduced the space between the two side walls making it more difficult to make the connection. It also made it more difficult to disassemble the wall panels as the bolts were binding against the u-shaped insert due to its deformation. This could be prevented by inserting a spacer in the u-shaped inserts during fabrication. Similarly, a material other than Styrofoam should be used in the u-shaped inserts to prevent concrete from entering during casting. When removing the Styrofoam from the u-shaped inserts, pieces of it stay stuck in the cap nuts after the bolts were also taken out. This could be combined with the spacer to prevent deformation of the u-shaped inserts and for commercial applications be made from a reusable material to allow for repeat uses.

The connection could also be improved by designing the z-plates with a stop. During the assembly of the wall panels, the alignment bolt in the connecting wall panel was able to slide past where it was intended to rest. This meant that as the horizontal connections were made between lower wall panels, the alignment bolt for the connection at the bottom of the wall panels slid too far and there was an uneven gap between the wall panels, which made it harder to make the connection. This was improved during testing as the connection was reattempted with a stop welded in place. The connection was noticeably better on this iteration. An example of the z-plate adjusted during testing and a potential updated design for the z-plate including a stop is shown in Figure 6.

(a) Welded prototype (b) Updated design with stop

Figure 6: Z-plate with stop

6 Conclusions and Recommendations

The purpose of this paper was to evaluate the constructability of precast wall assemblies using a new self-aligning bolted connection by comparing it to grout sleeve connections that are commonly used in precast construction. In particular the ability for the new connection to address tolerance errors, that are prevalent in precast concrete construction, was assessed as well as the overall fit of the connection, when assembling three wall panels.

- The self-aligning connection reduces tolerance errors by connecting steel frames in the concrete wall panels rather than connecting concrete wall panels themselves. That leads to overall improved accuracy reduces the need for levelling and shimming as often done in traditional precast construction methods. The self-aligning connection was laser cut for accuracy and used 1/64 in. (0.4 mm) tolerances at the bolt holes which can be compared to the recommended tolerances for precast concrete wall panels which are ¼ in. (6.35 mm) for width and ½ in. (12.7 mm) for length.

- The use of the self-aligning connection reduces the project duration by reducing the number of overall steps needed in the assembly process, particularly labour-intensive steps that occur on-site including adjustment of the connection components, levelling, and shimming.

- This connection may be able to improve the assembly efficiency as it does not require installation of separate lifting points during fabrication. It will likely require less time and quantity of bracing during assembly compared to tradition precast construction using grout sleeve connections.

- The self-aligning connection requires stricter tolerances around the bolt holes to prevent rotation of the z-plate during assembly.

- Overtightening of the bolts in the u-shaped insert during fabrication causes binding between the bolts and the u-shaped insert which should be prevented by installing a spacer in the u-shaped insert during fabrication.

- The design of the z-plates can be improved by installing a stop on the top and bottom of the middle plate to prevent the alignment bolts from sliding past their intended location.

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