Wall-to-floor interaction in concrete buildings with rocking wall systems

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ABSTRACT: Previous research has shown that rocking or self-centering precast concrete walls provides superior seismic resistance when compared to traditional concrete construction. However, uplift at the base of the wall causes a vertical displacement incompatibility between the wall and floor diaphragms. The type of wall-to-floor connection and the floor diaphragm's resistance to wall uplift can have a significant influence on the seismic behaviour of both the wall and the building. Finite element modelling indicated that the lateral strength of a building is significantly increased when the floor diaphragms are rigidly restrained to the rocking wall. Additionally, reparable damage is caused to the floor slab when a cast-in-place connection is detailed. An alternative to a rigid cast-in-place connection is to use a wall-to-floor connection that will isolate the floor from the vertical displacement and rotation of the wall, preventing any significant floor damage. The influence of the wall-to-floor interaction on the seismic response of a building is not limited to rocking walls, and has the potential to be more severe for traditional reinforced concrete walls, increasing the vulnerability of the wall to shear or axial failure.

1 INTRODUCTION

The behaviour of lateral load resisting shear walls is often investigated in isolation from the other structural and non-structural elements in a building. However, the entire structure needs to be analysed to fully appreciate the expected seismic behaviour of a building. For example, Waugh and Sritharan (2010) found that the inclusion of the floor diaphragms and gravity columns into an analytical building model was critical in order to accurately predict the dynamic response of a seven storey reinforced concrete building.

When a low-damage structural building system is being designed, such as a rocking self-centering wall, accounting for interaction between the structural elements is critical to ensure that the desired performance targets of the structure can be achieved during an earthquake. There is no advantage in designing a seismic resilient wall system if extensive damage is likely to occur in other parts of the structure, which is likely to compromise the self-centering ability of the building following an earthquake. A critical consideration when examining the seismic response of a self-centering building is how the wall system interacts with the floor diaphragms and the effect that this interaction has on the overall seismic performance of buildings. Although the discussion below is focussed on a self-centering wall system, the issues raised in this paper are applicable to all types of buildings. The recent Canterbury earthquakes have highlighted that the interaction between the wall and the surrounding structural elements is also a significant issue for buildings with traditional reinforced concrete (RC) walls. The poor performance of several RC walls during the Canterbury earthquakes has been partially attributed to the elongation of the wall, which when restrained by the floor diaphragms, results in an increase in axial and shear loads acting on the wall (Canturbury Earthquakes Royal Commission 2011; Structural Engineering Society of New Zealand (SESOC) 2011).

When subjected to a lateral load, the flexural deformation of a self-centering wall is concentrated at a single crack that opens up at the base of the wall, as shown in Figure 1. The uplift at the base of the wall causes a vertical displacement and rotation at the location of the wall-to-floor connections. To ensure that a seismic resilient building is achieved, the vertical displacement incompatibility at the wall-to-floor connections needs to be accounted for when designing both the floor diaphragms and the wall system resisting the lateral earthquake loads.

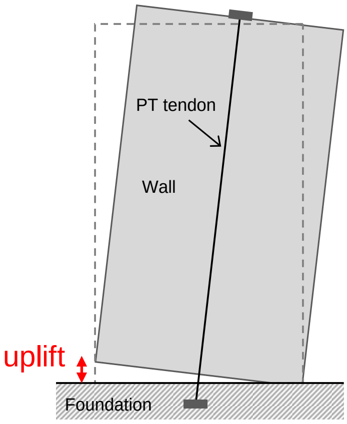


Figure 1 – Lateral load behaviour of a post-tensioned rocking wall

2 BACKGROUND

Previous research into low-damage concrete building systems has resulted in the development of several different rocking wall systems, including individual post-tensioned concrete walls (Kurama et al. 1999; Perez et al. 2007; Henry et al. 2012), hybrid walls (Kurama 2002; Holden et al. 2003; Marriott et al. 2008), jointed walls (Priestley et al. 1999; Sritharan et al. 2007), and precast walls with end columns (PreWEC) (Sritharan et al. 2008). Predominantly these wall systems have been designed, analysed, and tested as individual structural elements and minimal research has been conducted to investigate the seismic behaviour of wall-to-floor connections. In the few research projects that involved experimental testing of building systems that utilised self-centering precast concrete members, such as the PRESSS five storey building (Priestley et al. 1999) and shake-table testing of a precast concrete building (Schoettler et al. 2009), special connections were used to isolate the floors from the wall uplift in order to minimise the uncertainty in the behaviour.

Several design standards and guidelines have been published in both New Zealand the United States that relate to the seismic design of self-centering precast concrete wall systems (NZS 3101:2006 ; ACI Innovation Task Group 5 2007; ACI Innovation Task Group 5 2009; Pampanin et al. 2010). However, these documents primarily focus on the wall component behaviour, and simply state that the interaction between structural elements, including wall and floor diaphragms, needs to be considered during the seismic design of a building with self-centering components.

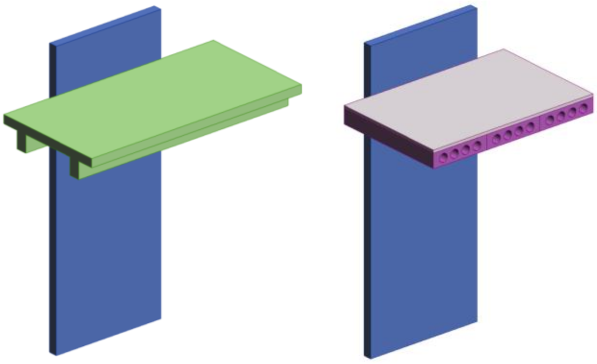
3 WALL-TO-FLOOR CONNECTION DETAILS

The type of wall-to-floor connection determines how the lateral inertia forces from the diaphragm are transferred to the wall, as well as how the floor diaphragms respond to vertical uplift of the wall. In this study, three types of wall-to-floor connections have been identified based on the type and orientation of the floor system:

1. Cast-in-place floors (rigid wall-to-floor connection)
2. Precast floor units spanning parallel to the wall (isolated wall-to-floor connection)
3. Precast floor units bearing on the wall (semi-rigid wall-to-floor connection)

A cast-in-place wall-to-floor connection would be constructed using reinforcing bars that extend from the precast wall into the floor slab, providing a moment resisting connection where the floor diaphragm would be constrained to deform with the wall system. A concern with the cast-in-place connection detail is that the floor slab around the wall could be damaged when the wall rocks, such that the lateral and gravity load paths between the floor and the wall could be compromised.

With precast concrete floor construction, the connection type depends on the orientation of the floor units and the load paths that are selected. If precast concrete floor units span parallel to the length of the wall, as shown in Figure 2a, then the concrete shear wall may not be required to carry vertical gravity loads from the floor area. However, the seismic inertia forces generated in the floor diaphragm must be transferred to the lateral load resisting shear wall. If the precast floor unit is connected to the wall using a rigid connection detail the relatively stiff precast floor unit will resist the uplift and rotation of the self-centering wall, which may have a detrimental effect on the wall behaviour. Alternatively, if the wall is not required to carry vertical gravity loads from the floor diaphragms, the wall-to-floor connection can be designed to transfer horizontal inertia loads with unrestrained displacement in the vertical direction. This type of isolated connection can be achieved using specially designed connectors. The use of a proprietary slotted connectors for precast concrete elements were previously used during experimental testing (Schoettler et al. 2009), however the connectors used were not specifically designed to handed the dynamic movement that occurred and consequently jamming occurred during the more severe tests.



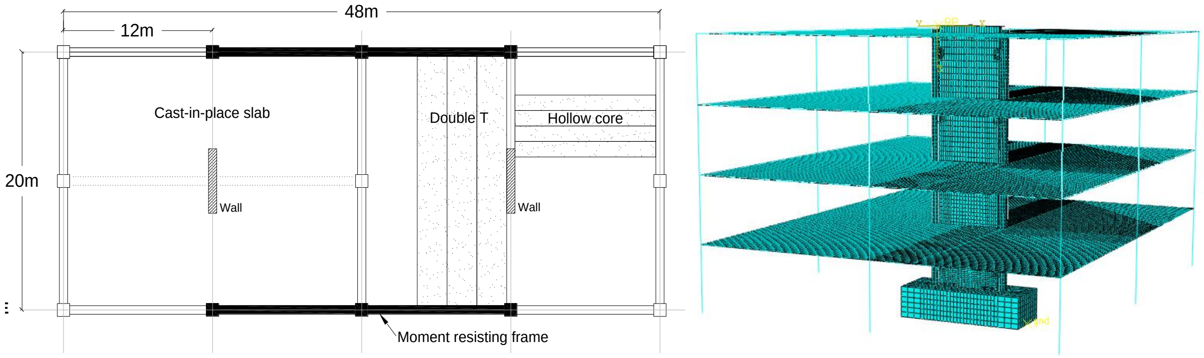
a) Parallel to the wall b) Bearing on the wall

Figure 2 – Wall-to-floor connections for precast floor units

When precast concrete floor units are orientated perpendicular to the length of the wall, as shown in Figure 2b, the wall is required to carry both vertical gravity loads and horizontal seismic inertia forces generated in the floor diaphragms. Because the wall is relied on for the gravity load path, the isolation type connection cannot be used. Typical detailing of a bearing connection would include the precast floor units seated on a corbel attached to the wall with an insitu concrete topping tying the floor diaphragm to the wall panel. When considering the seismic behaviour of the wall-to-floor connection with precast floor units bearing on the wall, the expected behaviour would be between that of the rigid cast-in-place connection and the isolated connection, with partial moment resistance provided by the insitu topping connection.

4 ANALYSIS OF A PROTOTYPE BUILDING

A prototype structure was designed to assess the seismic response of a building that included a self-centering wall system, with particular focus on the interaction between the wall and floor diaphragms. The layout for the four storey prototype building is shown in Figure 3a, with an assumed inter-storey height of 3.66 m. Lateral load resistance in the N-S direction relied exclusively on two shear walls. The shear walls were designed using the PreWEC rocking wall system of the same dimensions as that previously tested and analysed (Sritharan et al. 2008; Henry 2011). The PreWEC system consists of a precast concrete wall connected to two end columns using energy dissipating steel connectors. Additionally, the prototype building was designed with three possible options for the floor diaphragms, including a fully cast-in-place floor slab, precast double-T units spanning N-S and precast hollowcore units spanning E-W.



a) Layout　　　　b) FEM assembly

Figure 3 – Four-storey prototype building

4.1 *Finite Element Model*

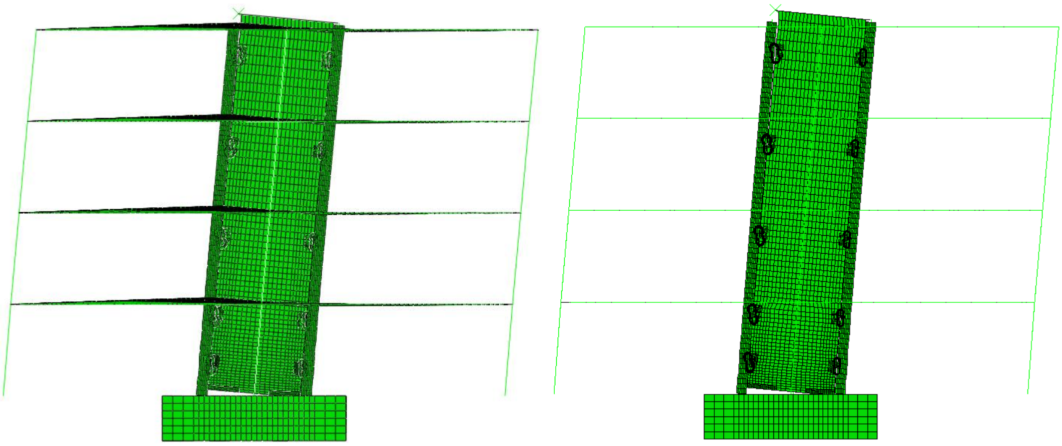
A finite element model (FEM) was developed to investigate the lateral load response of one half of the four storey prototype building, with both a rigid and an isolated wall-to-floor connection modelled. The PreWEC wall, which includes a wall, end columns, energy dissipating connectors, and post-tensioning tendons, was modelled using 3D solid brick elements. The floor diaphragms were modelled using plane-stress shell elements, and the beams and columns were modelled as wire beam and truss elements respectively. The "concrete damaged plasticity" model was used to define the non-linear behaviour of the concrete in both the wall and floor diaphragm, while the beams and columns were assigned elastic properties. The meshed assembly is shown in Figure 3b, and more detailed information on the prototype building FEM has been published by Henry (2011).

4.2 *FEM Results for Cast-in-Place Floor*

The first analysis was conducted to simulate the behaviour of a cast-in-place floor slab with a rigid wall-to-floor connection. The floor diaphragm shell element extended all the way through the concrete wall, and the cast-in-place connection was modelled using an embedded constraint to couple the floor nodes within the connection region to adjacent nodes of the wall.

The deformed shape of the building FEM with the rigid wall-to-floor connection is shown in Figure 4a at 3% lateral wall drift. The PreWEC wall behaved in the same manner as the FEM of the individual PreWEC specimen (Henry 2011), with deformation primarily concentrated at the single crack at the wall base. The rigid behaviour of the cast-in-place wall-to-floor connections is visible, with the floors constrained to uplift and rotate with the wall. Because the edges of the floor were constrained to the gravity load resisting frame, which did not experience significant vertical displacement, the uplift and rotation at the wall-to-floor connection caused out-of-plane bending of the floor diaphragm.

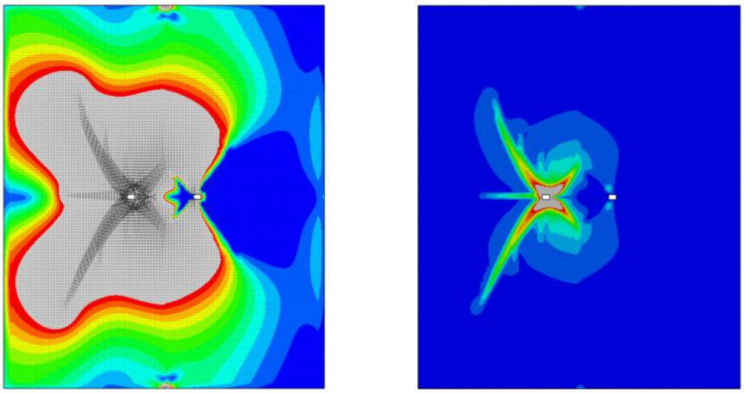
The principal concrete strains in the top surface of the level 4 floor are plotted in Figure 5a where tensile strains that exceed the concrete cracking strain are represented by the grey region. At 2% lateral wall drift, which corresponds to the design level lateral displacement, the area of the cracked concrete is significant and covers in excess of 30% of the floor area. However, strains of a large magnitude are confined to a small region directly adjacent to the end of the wall. To determine how wide the cracks in the floor slabs would open, strain magnitudes in the steel reinforcement were investigated. The FEM calculated maximum strains in the top layer of reinforcing steel in the level 4 floor slab are plotted in Figure 5b, with strains exceeding the yield strain of the reinforcing steel represented by the grey region. At 2% lateral drift only a small portion of the reinforcing steel was expected to yield, which indicated that most of the concrete cracks should close up when the load is removed. Additionally, the maximum tensile strain at 2% drift was only 0.0098, which is just below the seismic serviceability limit strain of 0.010, as suggested by Priestley et al. (2007). Consequently, the damage to the floor slab would result in residual crack widths being less than 1.0 mm, which are easily repaired. However, yielding of the reinforcement results in hysteretic energy dissipation, which combined with the residual crack width, may result in larger residual displacements and a loss of the wall system's self-centering advantage.



a) Cast-in-place connection

b) Isolated connection

Figure 4 – Elevation view showing the displaced shape of the prototype building FEM (magnified 3 times)



(a) Principal strain contours

(b) Reinforcing steel strains

Figure 5 – Calculated principal strain contours of the top cast-in-place floor slab at 2% lateral drift

The monotonic moment-drift response calculated from the FEM of the prototype building with cast-in-place (CIP) floor is plotted in Figure 6, alongside the FEM response of just the PreWEC wall (ignoring the floors and gravity frame). It can be seen that the inclusion of the floors significantly altered the response, with the deformation and framing action of the floor diaphragms increasing the moment resistance of the building by approximately 44% at 2% lateral wall drift and by approximately 50% at 3% lateral wall drift. This overstrength, which is routinely ignored in design, would have a significant effect on the seismic response of the wall and building, particularly when considering capacity design principles. The increased moment resistance resulted in an increased shear demand on the PreWEC wall, which could lead to undesirable failure mechanisms such as shear failure or base sliding of the wall panel. Clearly the influence of the floor diaphragm should be considered and quantified during the design process and that analysing a wall by itself is not sufficient, even when the wall is the primary lateral load resisting structural element.

4.3 *FEM Results for Isolated Floor*

In addition to the rigid cast-in-place connection, a fully isolated wall-to-floor connection was also modelled. This isolated connection represented the use of a special connector that will isolate the floors from the vertical uplift of the wall while still providing a load path for the horizontal inertia forces. To achieve the isolated connection in the FEM, a cut-out gap was provided in the floor diaphragm around the entire PreWEC wall and the horizontal displacements of floor nodes at four discrete locations were coupled to the corresponding node of the wall while leaving the vertical displacements unconstrained.

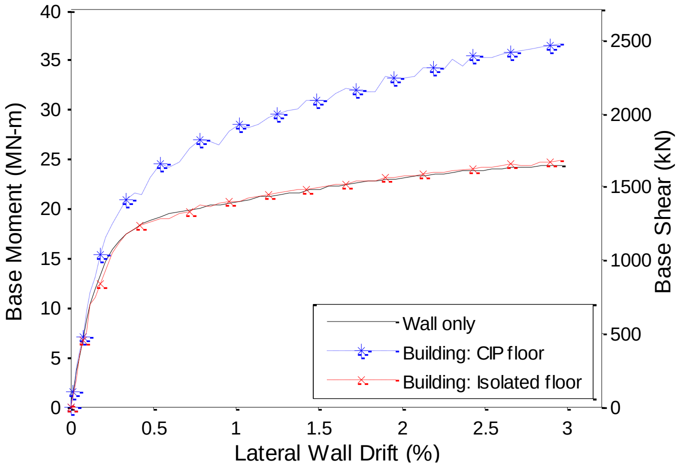


Figure 6 – Calculated response of the prototype building FEM with both cast-in-place and isolated floors

The deformed shape of the building model with isolated floors is shown in Figure 4b at 3% lateral wall drift. Unlike the cast-in-place connection, the uplift and rotation of the wall was not transferred to the floors, and as a result the floor diaphragms remained relatively undeformed as they displaced horizontally with the wall. A closer inspection confirmed that no significant damage occurred to the floor diaphragms with the predicted strains not exceeding the concrete cracking strain at any location.

As well as preventing damage to the floor diaphragms, the isolated wall-to-floor connection resulted in a more predictable and dependable lateral strength. Figure 6 shows a comparison of the moment-drift response of the building with an isolated wall-to-floor connection, alongside the response of only the PreWEC wall and the building with a cast-in-place (CIP) wall-to-floor connection. Unlike the cast-in-place connection, which showed a significant increase in strength, the response of the building with isolated floor connections is almost identical to the analysis of the individual PreWEC wall. This similarity means that when the floors are isolated, the entire lateral resistance is provided by the PreWEC system and the seismic response of the building can be calculated with a high level of confidence.

5 REINFORCED CONCRETE (RC) WALLS

As stated earlier, wall-to-floor interaction is also an important consideration for RC walls. The recent Canterbury earthquakes and previous research has highlighted the effect that wall-to-floor interaction can have on the seismic response of buildings with RC walls (Anon 1988; Rodriguez and Blandon 2005; Waugh and Sritharan 2010). To investigate the potential effect of wall-to-floor interaction on the seismic response of buildings with RC walls, the experimentally tested PreWEC wall (Sritharan et al. 2008) that was used in the FEM analysis described above was compared with a previously tested RC wall specimen RWN (French et al. 2005-2008). Direct comparison between these two wall specimens is possible because the PreWEC wall was intentionally designed to be equivalent to the RWN wall in terms of dimensions, material properties, and design capacities. A comparison between the measured elongation for each positive cycle peak at both the north and south edges of the top of the PreWEC and RC wall specimens is plotted in Figure 7. The elongation for the RC wall is up to twice that of the PreWEC at the north edge of the wall. This larger elongation is expected for a RC wall because the nonlinear behaviour in the plastic hinge results in a large number of distributed cracks that do not completely close on reverse cycles compared to uplift at the existing wall-to-foundation joint for the PreWEC specimen. The residual cracks also resulted in a large 20 mm permanent elongation to the RC wall at the conclusion of the test compared with a 2 mm permanent elongation for the PreWEC specimen. Lastly, the neutral axis location at the base of the PreWEC wall caused a significant negative elongation at the south edge of the wall. This negative elongation means that the floor diaphragms are pushed up at the north edge and pulled down at the south edge, resulting in minimal change to the wall axial load. The larger elongations of the RC wall at high lateral drifts, combined with a large permanent elongation means that in addition to an increased shear demand, the axial load on the RC wall will also increase beyond that expected during design. This high axial load increases the chance of compression or buckling failure of the wall toe.

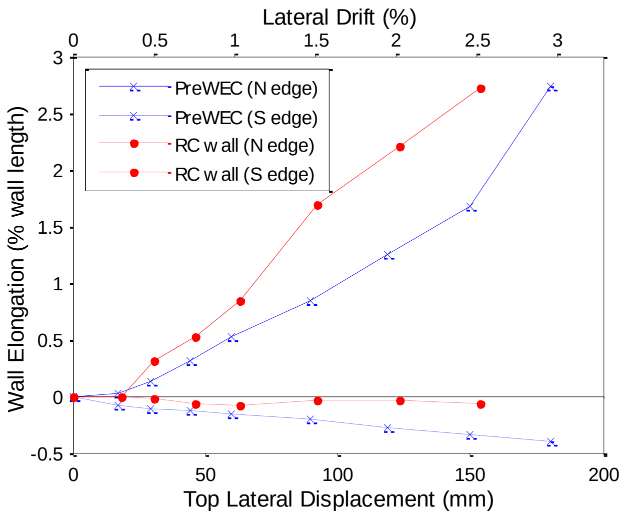


Figure 7 – Comparison of the measured elongation from the PreWEC and RC test walls

6 CONCLUSIONS

Although several self-centering systems including precast concrete wall concepts have been successfully developed, the interaction between the self-centering systems and the surrounding structure has previously received little attention. As a self-centering wall is displaced horizontally, uplift occurs at the base, causing a relative vertical displacement and rotation at the wall-to-floor connections while the edges of the floor are restrained vertically by the gravity columns. The wall-to-floor connection is dependent on the type of floor system used, with the two extreme cases being a rigid cast-in-place connection and a fully isolated connection.

Finite element modelling of a four storey prototype building with a rocking wall indicated that when a rigid cast-in-place wall-to-floor connection was used, the deformation of the floor diaphragms was significant. Although extensive cracking of the concrete floor and some yielding of the reinforcing steel was predicted at the 2% design level lateral drift, the damage would typically be within serviceability limits and thus should be easily repairable. The lateral load response of the building model was dramatically altered when the wall-to-floor interaction was accounted for, with up to 50% increase in the lateral strength at the design level lateral drift. This overstrength has potential consequences for the seismic design of the building and can cause undesirable shear or sliding failure of the wall. In contract to a rigid cast-in-place connection, finite element modelling indicated that the isolated wall-to-floor connection can effectively eliminate any damage to the floor diaphragm and also provide a more dependable and predictable lateral strength.

The influence of the wall-to-floor interaction is also significant for buildings with traditional RC walls. A comparison between experimental data from a precast self-centering wall and a monolithic RC wall indicated that the total wall elongation can be up to two times higher for the RC wall. The wall-to-floor interaction could have more severe effects on the performance of an RC wall due to the increased shear and axial loads, which increase the possibility of brittle wall failure.

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