Conceptual development of demountable floor-frame connections to avoid earthquake damage on precast floors

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ABSTRACT

The performance of multistorey buildings with precast concrete flooring systems in past earthquakes has exposed numerous drawbacks. The monolithic connection between precast floors and frames causes displacement compatibility demands that cannot be accommodated by typical detailing, resulting in severe damage around the floor-frame interface that is not technically or economically viable to repair. Furthermore, the typical connection adds uncertainty to the structural design, as it leads to a slab contribution to the earthquake-resistant system that is difficult to quantify. This paper reviews the seismic damage to buildings with precast concrete floors in New Zealand and proposes a novel way to avoid it by detaching the floors from the frames with slotted steel connections to replace the conventional monolithic connections. These slotted steel connections are designed to allow the transfer of inertial forces, while accommodating the relative displacements between the floors and the frames. This paper proposes the conceptual design of the slotted steel connections by considering the largest displacements expected to be developed in frame building structures as well as the largest inertial forces that occur when the building reaches its lateral capacity.

1 INTRODUCTION

Recent earthquakes have exposed numerous drawbacks of the commonly used monolithic connections between precast concrete floors and beams. In New Zealand, the 2010/2011 Canterbury earthquake sequence and the 2016 Kaikoura earthquake showed that the displacement compatibility demands between the floors and the lateral load resisting system (LLRS) cause extensive damage in the slab topping that can lead to collapse (Corney et al., 2014; Henry et al., 2017). Moreover, the damage incurred was often not technically or economically viable to repair, leading to many damaged buildings needing to be demolished.

In response to the poor performance of precast flooring systems, updated detailing and construction requirements were included as amendments to the New Zealand 3101 Concrete Structures Standard (Standards New Zealand, 2017), including increasing the seating length to avoid loss of seating failure and requiring ductile detailing. Additionally, retrofitting methods have been developed to reduce the risk of collapse of existing buildings that do not meet the updated criteria (Elwood et al., 2022). However, these methods do not avoid damage to the precast floor.

This paper proposes a novel low-damage floor-frame connection, which uses discrete slotted steel angles to connect the slabs to the beams. These connections allow the precast floor units to remain flat and thus achieve low damage by not forcing them to follow the deformation profile of the beams. Therefore, the proposed floor-frame connections can be used in demountable buildings and act as a retrofitting method for existing buildings, while avoiding the damage that has been identified in previous earthquakes.

2 BACKGROUND

2.1 Damage observed in past earthquakes

The damage observed in past earthquakes in precast flooring systems can be explained by the lateral displacement compatibility demands that the floors suffer due to their monolithic connection with a cast on-site topping. As the frames deform laterally, the floors are forced to follow the same deformation profile along the floor-frame interface, inducing large stresses on the thin topping. Figure 1 shows the vertical deformation incompatibility, along with typical observed crack distributions.

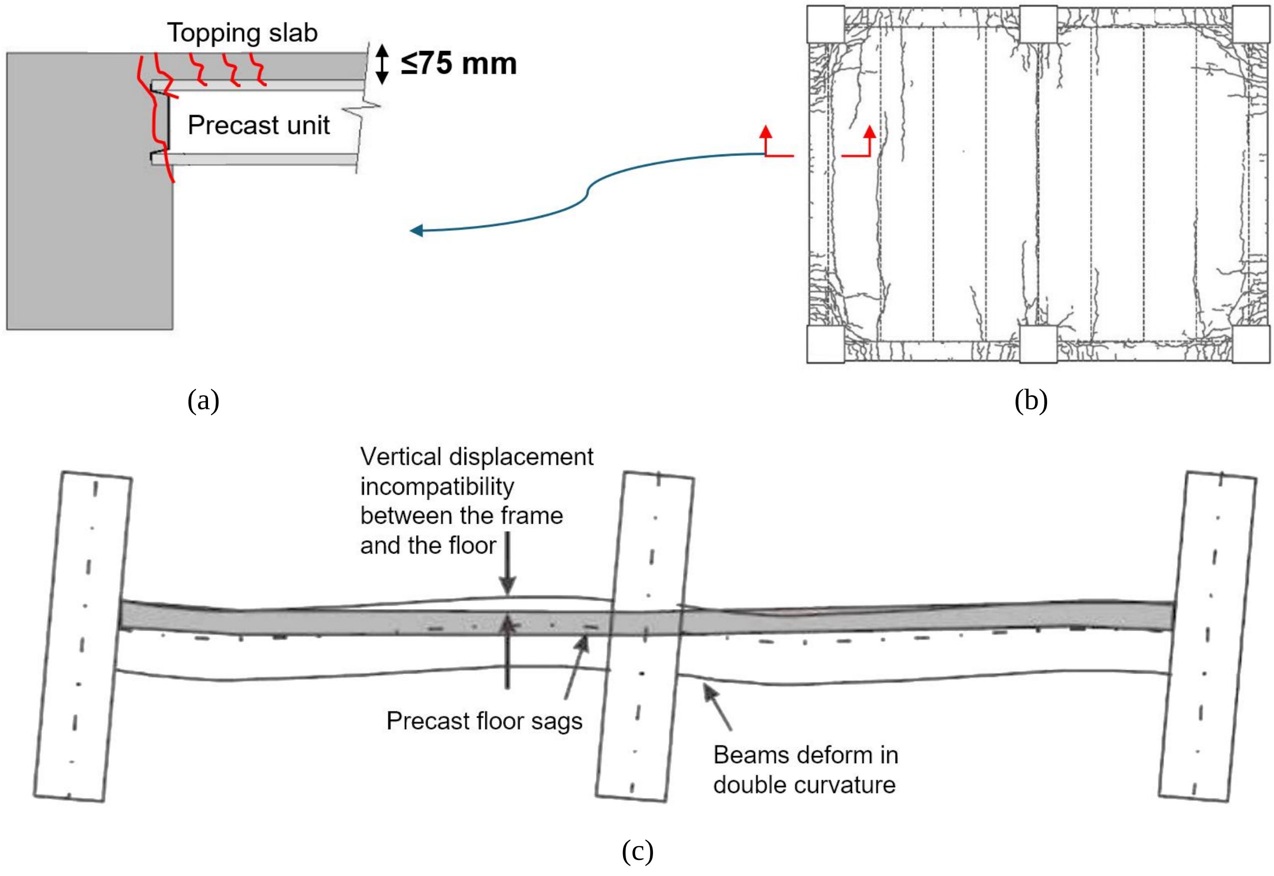


Figure 1: Precast floor damage caused by compatibility demands: (a) typical precast floor section, (b) example of observed damage in plan (Büker et al., 2022b), and (c) elevation of the vertical displacement incompatibility (Matthews, 2004).

In addition to the vertical displacements, the floors are subjected to compatibility demands due to the inwards rotation of the beams, leading to positive moment failure and delamination of the precast unit (see Figure 2(a)), and outwards rotation, leading to negative moment failure (see Figure 2(b)).

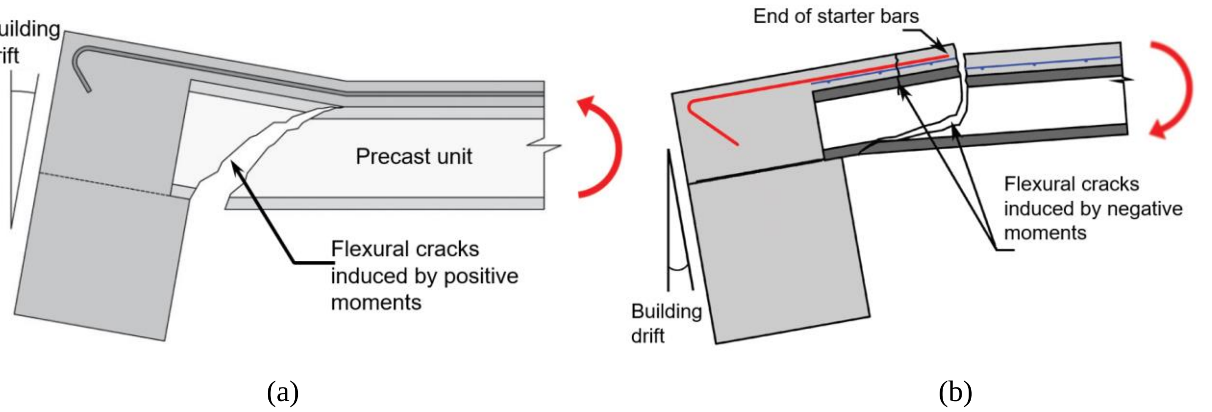


Figure 2: Beam rotation compatibility demands: (a) inwards rotation (Büker et al., 2022b) and (b) outwards rotation (Sarkis et al., 2022).

Moreover, it is now a well-understood phenomenon that when ductile concrete frames undergo repeated cycles of inelastic deformations, the reinforcement in tension does not return to its original length, causing the hinge zones to elongate. This has caused precast floor units to lose seating in the past, leading to collapse, as beam elongation was not considered in determining the required seating length. Examples of precast floors collapsing due to the increased span length caused by beam elongation are the parking building of the Meadows Apartment during the 1994 Northridge Earthquake (Norton et al., 1994) and the Statistics House Building during the 2016 Kaikoura Earthquake (Henry et al., 2017).

2.2 Existing design approach

For both new buildings and the retrofitting of existing ones, the existing design approaches specify increasing the seating length to avoid loss of seating failure and increasing the ductility and strength of the connection to avoid shear and bending damage.

For new buildings, the NZS 3101 code requirements (Standards New Zealand, 2017) include considering a seating length of at least 75 mm to reduce the risk of loss of seating failure, using low friction bearing strips to reduce spalling and to allow some minor sliding, using continuity reinforcement to avoid a weak section susceptible to negative moment failure, and checking the shear strength of the floor against the estimated demand (Corney, 2018). Although increasing the seating length has proven to be effective in avoiding collapse, this has not avoided extensive damage. Similarly, adding continuity reinforcement will move the weak section away from the support but it cannot avoid damage (Brooke et al., 2022), such as cracking or eventual fracture of the bars (Parr et al., 2022b). Finally, it is difficult to estimate both the shear demand and strength of the floor-frame interface to confidently ensure the capacity > demand hierarchy.

For retrofitting existing buildings, a similar philosophy has been followed. Buildings that do not have the required seating length have been retrofitted with steel elements that serve as supplementary seating (see Figure 3), and floors constructed with detailing that leads to low strength and ductility have been reinforced with hangers and FRP sheets (Elwood et al., 2022). Despite avoiding collapse and reducing damage at low drifts, when the lateral drifts increase, severe damage in the floors could not be avoided by this retrofitting method (Parr et al., 2022a).

(a) (b)

Figure 3: Conventional retrofitting methods for precast floor: (a) supplementary seating (Henry et al., 2017) and (b) strong back supports (Büker et al., 2022a).

Although the updated detailing requirements and the currently used retrofitting methods improve the seismic performance of precast floors and reduce the risk of collapse, they cannot prevent damage. Moreover, when the building is subjected to a strong earthquake, the additional strength provided by the connections will impose a larger force on the lateral load resisting components of the building, which can be detrimental. Similarly, the retrofitting methods can increase the strength of the beams, which could alter the strength hierarchy of the system (beams weaker than the columns, designed to yield at their ends), leading to the formation of non-ductile mechanisms (Dhakal, 2008).

3 CONCEPTUAL DEVELOPMENT OF A NEW LOW-DAMAGE CONNECTION

In this study, a novel low-damage connection that allows relative movement between the floor and beams is proposed to replace the conventional rigid connections. Using low friction bearing strips and slotted steel elements allows the movement and sliding of the precast floor relative to the beams, which will permit the system to accommodate the imposed deformational demands, thus avoiding damage. The connection will also need to be able to transfer the inertial forces from the slabs to the beams, and provide diaphragm action. This concept can be used in the design of new buildings with a conventional LLRS, in next-generation demountable buildings with dry connections between structural elements (Aninthaneni, 2017), and as a retrofitting method to existing buildings, by saw-cutting the topping and starter bars connecting the floors to the beams, as long as the negative moment is not required to resist the gravity loads.

3.1 Low-damage floor-frame connections

The concept of the proposed low-damage floor-frame connections is schematically illustrated in Figure 4 for a concrete frame structure with intermediate columns. The floor units are labelled U1 to U10 and are separated by dashed lines. The connection consists of steel angles with slots both in the vertical and horizontal planes located discretely along the beams and away from the plastic hinge regions. The vertical slot allows the floor to accommodate the vertical beam deflections, allowing the beam to deform in double curvature while the slab remains flat. The horizontal slot is oriented perpendicular to the beam it is connected to, allowing the elongation of the beams perpendicular to the slot, while transferring the lateral inertial forces in the direction parallel to the beams. The floor units will be connected either with a conventional concrete topping in existing buildings, or with shear keys or steel elements in new buildings, but will be separated at the location of intermediate columns to allow for the elongation of plastic hinges, as shown in Figure 4. The connections to the parallel beams are steel angles anchored to both the slab and the beam and a low friction bearing strip is used between the steel element and the floor. For the support beams, the angles are reinforced with triangular side plates to provide them with additional strength to take gravity loads, and having the anchors placed at the top of the vertical slot, allowing them to serve as supplementary seating.

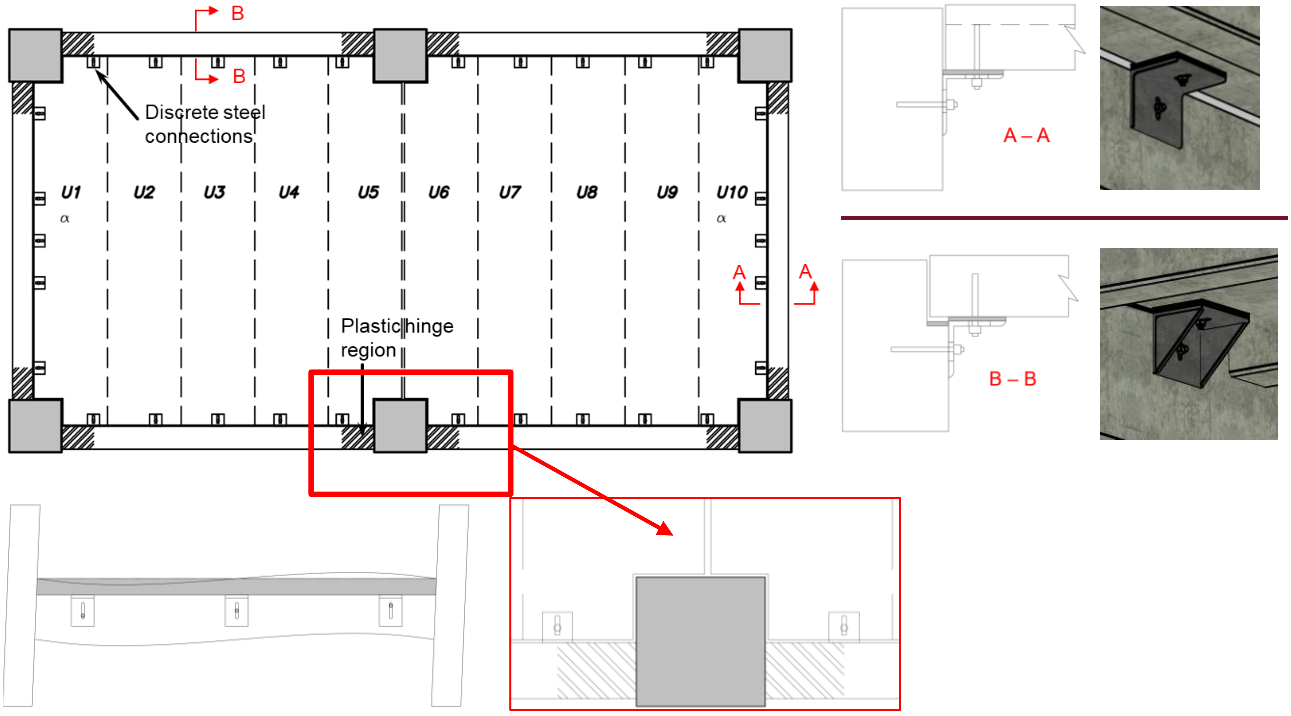
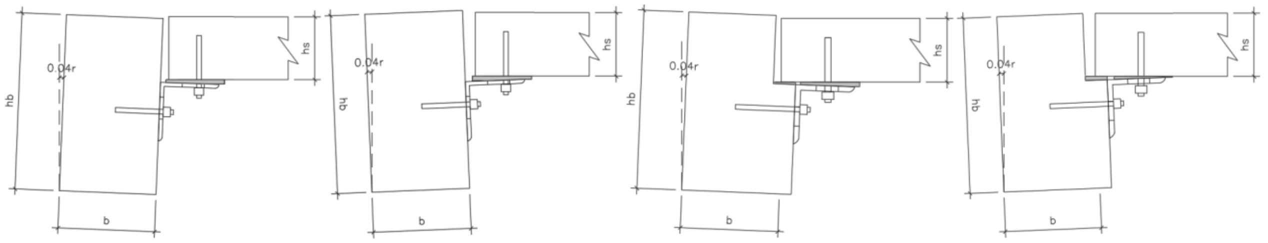


Figure 4: Low-damage demountable connection concept, accommodation of vertical and in plan displacements.

3.2 Demands and capacity

The magnitude of the relative displacements and the corresponding size of the slots can be estimated using simple geometry, and considering the maximum displacements a ductile building would be able to undergo. To avoid damage to the floors in strong earthquakes, an interstorey drift of 4% will be considered as an upper boundary of the drifts during a Maximum Considered Earthquake (MCE) for a collapse prevention performance level. The beam deflections can then be calculated using elastic analysis as a conservative assumption considering the curvature to be distributed along the whole length of the beam. In reality, the beams will deform inelastically which would concentrate the curvature at the ends of the beams, leaving the middle part of the beam mostly flat, reducing the vertical relative displacement demands. With these assumptions, a vertical slot size of 0.005 L, where L is the clear length of the beam, was found to be enough to accommodate the vertical relative displacements.

The horizontal slot is required to accommodate relative displacement between the floor and the frame due to a combination of the elongation of the beam parallel to the slot and the rotation of the beam the steel element is connected to. Beam elongation can be estimated using simple expressions such as the one provided in the New Zealand Standards 3101, which is an upper bound estimate for the elongation during an MCE, and can be calculated as 0.0036 h, where h is the depth of the beam. The rotation of the beam will be considered as 0.04 radians for a 4% interstorey drift, using these values. The required length of the horizontal slot can be estimated using simple geometry. Adding the rotation demand with the beam elongation demand results in a horizontal slot size of 0.044 h. Figure 5 shows an example of how the relative displacements of both beam rotation and beam elongation can be accommodated by the slots in the connections and the compression of the bearing strip.



(a) (b) (c) (d)

Figure 5: Accommodation of rotations and beam elongation: (a) inwards and (b) outwards rotation of parallel beam, and (c) inwards and (d) outwards rotation of support beam.

During an earthquake, the floors act as diaphragms that tie the elements of the LLRS together and transfer the inertial forces to them. The proposed connection uses slots oriented perpendicular to the beams it is connected to, but allows the transfer of forces in the parallel direction. The anchors and steel elements can be designed to take these inertial forces, resulting in similar load paths as in conventional buildings.

The connections are designed as force-controlled to remain undamaged, therefore requiring an upper bound estimate of the inertial forces they will need to transfer. One way to achieve this is by estimating the lateral capacity of the building, considering overstrength, and then estimating the inertial forces at each floor that would lead the building to reach its capacity. A simple method to do this estimation based on an assumed distribution of vertical loads can be found in Pujol et al. (2022). Conservatively, the maximum of the obtained inertial forces corresponding to different load distributions can be used for the design of the floors.

Another method to estimate the inertial forces is to design the floors as acceleration sensitive components, for which codes such as the New Zealand Standards 1170.5 (Standards New Zealand, 2004) give simple expressions to estimate the acceleration coefficient that considers the overstrength of the building and dynamic effects. This approach is simpler but also very conservative, leading to large forces that require more connection points.

Finally, once the forces in the floors are estimated, they will need to be distributed to the number of connections used in that direction. A uniform distribution among the connection points can be considered, although it may not reflect the real distribution of forces due to the diaphragm and connection flexibility. Then, different failure modes, such as concrete pullout, shearing and fracture of the anchors, and yielding of the steel angles will need to be considered. It can be seen that the anchors will be subjected to a combination of tension and shear, and the steel angles to a combination of bending, shear and torsion.

4 CONCLUSIONS

This paper presents a potential solution to address problems previously identified in multistorey buildings with precast concrete floor units. These problems are caused by displacement compatibility demands, which is due mainly to the way they are constructed. As the floors are monolithically connected to the LLRS, they are forced to deform vertically following the deflection profile of the beams, to bend when the support beams rotate, and to extend when the beams elongate, causing large stresses that result in extensive damage. The conventional approach to avoid collapse and reduce damage has been to extend the seating length of the floor units, and to increase the strength and ductility of the connections to the beams, although the very thin topping used is very limited in its strength and deformation capacity. It has been seen that this approach does not avoid severe damage in the floors at large drifts.

To circumvent these problems, this paper summaries the conceptual development of a novel low-damage connection that allows relative displacements between the floors and the frames, permitting the floors to remain flat and undamaged, while the beams deform as they were intended in the design phase of the building. The connections will be designed to: (i) accommodate the relative displacements between the floors and the frames, (ii) transfer the earthquake inertial forces, and (iii) provide diaphragm action to the system. This is achieved by using a number of discrete connections to both the parallel and support beams, consisting of steel angles with horizontal and vertical slots anchored to both the beams and the floors. These discrete connections:

a. Should have slotted holes sized to accommodate the horizontal relative displacements of the floor units as large as 0.044 h, where h is the depth of the beam
b. Should have slotted holes to accommodate the vertical relative displacements as large as 0.005 L, where L is the clear length of the beam, and
c. Should be sized to resist inertial forces estimated from a limit analysis conducted assuming a lateral distribution of external forces and considering probable material properties (i.e. considering potential "overstrength").

This paper has presents only the background of the problem and the conceptual development of the proposed connection, and the details of its design, as well as its validation via numerical analyses and experimental testing, are currently progressing. However, the conceptual analysis suggests the connection to be a promising solution to the poor performance of precast flooring systems, while retaining their advantages, and allowing for the development of sustainable next-generation demountable buildings.

5 ACKNOWLEDGEMENTS

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REFERENCES

Aninthaneni P (2017). "Development *of a Demountable Precast Concrete Frame Building System for Seismic Regions"*. PhD Dissertation, Department of Civil and Natural Resources Engineering, University of Canterbury, 324pp. http://hdl.handle.net/10092/13676

Brooke NJ, Büker F, Bull DK, Elwood KJ, Henry RS and Hogan L (2022). "Overview of retrofit requirements and techniques for precast concrete floors". *SESOC Journal*, *35 No1*, 30–54. https://www.sesoc.org.nz/library/sesoc-journals/vol-31-35

Büker F, Brooke NJ, Hogan LS, Elwood KJ, Bull DK and Sullivan, TJ (2022a). "Design recommendations for strongback retrofits". *SESOC Journal*, *35 No1*, 69–85. https://www.sesoc.org.nz/library/sesoc-journals/vol-31-35

Büker F, Parr M, De Francesco G, Hogan LS, Bull DK, Elwood KJ, Liu A and Sullivan TJ (2022b). "Seismic damage observations of precast hollow-core floors from two full-scale super-assembly tests". *SESOC Journal*, *35 No1*, 125–148. https://www.sesoc.org.nz/library/sesoc-journals/vol-31-35

Corney SR (2018). "Seismic Performance of Precast Concrete Flooring Systems". PhD Dissertation, Department of Civil and Environmental Engineering, The University of Auckland, 330pp. http://hdl.handle.net/2292/36862

Corney SR, Henry RS and Ingham JM (2014). "Performance of precast concrete floor systems during the 2010/2011 Canterbury earthquake series". *Magazine of Concrete Research*, *66*(11), 563–575. https://doi.org/10.1680/macr.13.00106

Dhakal RP (2008). "Exploring the feasibility of a floor system detached from seismic beams in moment resisting frame buildings". *New Zealand Society of Earthquake Engineering (NZSEE) Conference*, 11 – 13 April, Wairakei, New Zealand, 16pp. http://hdl.handle.net/10092/2674

Elwood KJ, Brooke NJ and Hogan LS (2022). "ReCast Floors Project: overview and key recommendations". *SESOC Journal*, *35 No1*. https://www.sesoc.org.nz/library/sesoc-journals/vol-31-35.

Henry RS, Dizhur D, Elwood KJ, Hare J and Brunsdon D (2017). "Damage to concrete buildings with precast floors during the 2016 Kaikoura earthquake". *Bulletin of the New Zealand Society for Earthquake Engineering*, *50*(2), 174–186. https://doi.org/10.5459/bnzsee.50.2.174-186

Matthews J (2004). "*Hollow-Core Floor Slab Performance Following a Severe Earthquake". PhD Dissertation, Department of Civil and Natural Resources Engineering, University of Canterbury, 523pp. http://hdl.handle.net/10092/12896

Norton JA, King AB, Bull DK, Chapman HE, Mcverry GH, Larkin TJ and Spring KC (1994). "*Northridge Earthquake Reconnaissance Report: Report of the NZNSEE Reconnaissance Team on the 17 January 1994 Northridge, Los Angeles Earthquake*". Bulletin of the New Zealand Society for Earthquake Engineering, 27(4), 235–344. https://doi.org/10.5459/bnzsee.27.4.235-344

Parr M, Büker F, De Francesco G, Bull DK, Brooke N, Elwood KJ, Hogan L, Liu A and Sullivan T (2022a). "Load-path and stiffness degradation of floor diaphragms in reinforced concrete buildings subjected to lateral loading - Part I, Experimental observations". *SESOC Journal*, *35 No1*, 149–171. https://www.sesoc.org.nz/library/sesoc-journals/vol-31-35

Parr M, Bull D, Brooke N, De Francesco G, Elwood KJ, Hogan L, Liu A and Sullivan T (2022b). "Load-path and stiffness degradation of floor diaphragms in reinforced concrete buildings subjected to lateral loading – Part II, Data analysis". *SESOC Journal*, *35 No1*, 172–203. https://www.sesoc.org.nz/library/sesoc-journals/vol-31-35

Pujol S, Irfanoglu A and Puranam A (2022). "*Drift-Driven Design of Buildings; Mete Sozen's Works on Earthquake Engineering*". Taylor & Francis Group, 284pp. https://doi.org/10.1201/9781003281931

Sarkis AI, Sullivan TJ, Brunesi E and Nascimbene, R. (2022). "Strategies for finite element modelling of precast pre-stressed hollow-core floors". *SESOC Journal*, *35 No1*, 204–210. https://www.sesoc.org.nz/library/sesoc-journals/vol-31-35

Standards New Zealand (2004). "*NZS1170.5: Structural Design Actions. Part 5: Earthquake Actions - New Zealand*". Standards New Zealand, Wellington, 76pp. https://www.standards.govt.nz/shop/nzs-1170-52004-excludes-amdt-1

Standards New Zealand (2017). *"NZS 3101:2006 inc. A1-A3: Concrete Structures Standard"*. Standards New Zealand, Wellington, 76pp. https://www.standards.govt.nz/shop/NZS-3101-1-AND-22006-INC-A1-A2-A3