

REAL WORLD EXPERIENCE OF SEISMIC PERFORMANCE AND RETROFITS USED IN BUILDINGS WITH HOLLOW-CORE FLOORS

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ABSTRACT

Hollow-core floors have been recognised to have a potentially poor seismic performance since the 1994 Northridge earthquake, with subsequent research leading to significant developments in design and detailing requirements. Damage evaluations after the 2016 Kaikōura earthquake confirmed the expected seismic vulnerabilities in existing precast hollow-core floors and also revealed some previously unknown behaviour types. The Kaikōura earthquake provided significant impetus to advance our understanding of seismic performance of existing buildings with hollow-core floors and suitable retrofit solutions. Subsequently, the ReCast floors research programme was initiated. The reported work is one component of the ReCast floors programme in which investigations of the real-world performance of buildings with hollow-core floors was conducted. The objective was to collate information on damage patterns observed in buildings following the Kaikōura earthquake, the engineering characteristics of existing Wellington buildings with hollow-core floors, current strengthening status and the retrofit solutions implemented to help inform the ReCast research activities.

1 INTRODUCTION

Floors are integral parts of a building structure, and they play a significant role to meet life-safety objectives when subjected to different loading conditions. When considering gravity loads, the floors transfer vertical floor loads to the supporting members and also act to provide lateral restraint to ensure stability of vertical members, such as columns and walls. During earthquakes the floors also act as diaphragms to transfer the seismic actions across the buildings to lateral load resisting systems. As such, floors can be subjected to significant direct and indirect seismic actions. Direct actions result from the loads on floors, and indirect actions result from deformation compatibility between the supporting systems and the floors. The latter presents a great challenge for buildings with precast hollow-core floors that are stiff and brittle.

Hollow-core floors consist of precast hollow-core floor units and thin in-situ reinforced concrete topping. Although precast hollow-core floor units are one-way spanning elements between supporting members, the floor acts as a diaphragm in all directions to transfer seismic actions across the building in an earthquake. The diaphragm action of the floors is achieved by a thin in-situ reinforced concrete topping slab, where short starter bars are usually provided from the topping to the supporting members

along the edges of the floors, thus creating some degree of continuity along the slab edges.

There are many potential issues for hollow-core floor systems. Firstly, there are significant deformation incompatibility issues between one-way spanning hollow-core units and the two-way functioning in-situ topping slabs. This deformation incompatibility will induce shear actions between hollow-core units as well as between hollow-core units and in-situ slabs. The actions introduced to the floors could cause damage or failure to the precast hollow-core units. The local damage/failure of the floor systems could result in a localised collapse of the floor in addition to the loss of the lateral restraints to gravity supporting systems, leading to the instability of the primary supporting systems. Such damage could lead to progressive failure/collapse of the entire building. Therefore the vulnerabilities of hollow-core floors need to be addressed when assessing the seismic response and implementing retrofit or strengthening measures.

Concerns about the seismic integrity of precast concrete hollow-core floors constructed in New Zealand were raised following damage to similar floors during the Northridge earthquake in 1994. As a result, a research programme was funded to investigate the seismic behaviour of buildings with hollow-core floors constructed at that time (Matthews 2004, Lindsay 2004, Macpherson 2005, Jensen 2006, Wood 2008). One project of this research programme was the simulated cyclic loading

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test on a full-scale super-assembly of hollow-core floors supported by reinforced concrete frames, undertaken at the University of Canterbury (Matthews, 2004). The supporting details used in the test simulated the common practice in buildings constructed prior to 2003 using a 300 mm deep hollow-core floor. The test confirmed that hollow-core floors detailed at that time could be vulnerable in earthquakes and the observed evidence indicated serious gaps between assumed and actual behaviour of hollow-core floors of ductile frame buildings during strong earthquakes.

The Kaikōura earthquake in 2016 provided a reality check of existing buildings with precast floors. Partial collapse of precast concrete floors in the Statistics Building caused serious concerns about seismic resilience of buildings with precast floors (MBIE 2017, 2018), especially when the primary lateral load resisting systems are ductile frames. In response to these concerns, Wellington City Council established a Targeted Assessment Programme and a total of 64 mid-rise (5 to 15 storey high) reinforced concrete frame buildings with precast floors were assessed (Brunsdon et al., 2017).

An earthquake damage survey from the Targeted Assessment Programme revealed that hollow-core floors were more vulnerable to earthquake damage compared with other precast floor systems. The observed damage patterns confirmed the seismic vulnerabilities of older precast hollow-core floors as revealed in Matthews's test, and also revealed some previously unknown behaviour types (Henry et al., 2017). This brought about the realisation that reasonably modern buildings with hollow-core floors constructed before the mid 2000s may still experience significant damage and/or suffer collapse of the floors during a design level earthquake and potentially become the new class of vulnerable buildings in earthquakes.

Assessing the likely performance of precast floors presented a significant challenge for engineers. MBIE established a working group after the Kaikōura earthquake to revise and improve the available guidance for assessing precast floors. This guidance relied heavily on previous guidelines developed from research at the University of Canterbury (Fenwick 2010) as well as findings from the Canterbury and Kaikōura earthquakes. The guidance was included as an appendix to the technical proposal to revise Section C5 (Concrete Buildings) of the "Guidelines for Detailed Seismic Assessment of Buildings" (MBIE et al., 2018). Despite improved seismic assessment guidance, engineers also required urgent direction on appropriate retrofit approaches to address the identified vulnerabilities with precast floors. As a result the ReCast research programme was initiated (Brooke et al., 2019). As part

of the programme, there was a need to understand the existing retrofits being implemented by the industry to help inform the research direction. This paper details the investigation into the retrofits installed in hollow-core buildings in Wellington at the initiation of the ReCast floors project and included three objectives:

- To use the real-world experience from damage during the Kaikōura earthquake to help characterise the failure modes of hollow-core floors that require further investigation;
- To gain insights into the engineering characteristics of existing buildings with hollow-core floors to help inform the lab-based research and theoretical simulations; and
- To gain insights into currently implemented retrofit solutions associated with hollow-core floors.

2 CHARACTERISTICS OF EARTHQUAKE DAMAGE

2.1 GENERAL

A huge engineering effort was made during the Targeted Assessment Programme to assess seismic damage of the existing buildings with precast concrete floors in Wellington. The work within the Targeted Assessment Programme provided a large amount of valuable information. However much of the information collected remains confidential with only high level statistical information reported (Brunsdon et al., 2017). Surveying earthquake damage in buildings of interest was extremely difficult because of many concerns including health and safety. Consequently the intended effort for conducting the real-world investigations into Wellington buildings with hollow-core floors had many challenges.

To characterise the earthquake damage patterns observed in hollow-core floors at component level and global performance level, input was sought after the Kaikōura earthquake from engineers who had real-world experience in evaluating buildings with hollow-core floors. Input was also sought from contractors who were involved in demolishing or strengthening buildings with hollow-core floors. The engineering professionals provided insights into damage patterns in hollow-core floors and insights into the effects of global structural characteristics of a building on seismic damage in hollow-core floors, these insights not being easy to obtain from lab testing.

2.2 CHARACTERISTICS OF DAMAGE OBSERVATION IN HOLLOW-CORE FLOORS

Many of the damage patterns discussed with the engineers were covered previously in the report by Henry et al (2017). However, engineers and contractors also

highlighted other damage characteristics that were not previously reported, as follows:

- **Hidden web cracking and/or splitting of hollow-core floors**

Web cracking and web splitting is typically not visible from an external inspection. In a few buildings with no visible damage to hollow-core units, engineers confirmed the presence of web cracking/splitting by conducting investigations using borescope cameras.

- **Web cracking/splitting associated with incompatibility of the supporting systems**

A commonly reported phenomenon was that web cracking/web splitting was often associated with incompatible supporting systems at two ends of hollow-core units. For instance, hollow-core units that were supported by concrete frames at one end and block walls at the other end, or seismic resisting frames at one end and gravity frames at the other end. Incompatible supporting systems at the two support ends of hollow-core units may introduce torsion to the units, contributing to the damage to hollow-core webs.

- **Units supported on concrete masonry wall**

It was observed that there was severe damage to reinforced concrete masonry walls in buildings with reinforced concrete frame as the primary load resisting system. The damage included spalling/crushing of the reinforced concrete masonry walls in the areas supporting the precast floor units and severe diagonal shear cracking to the masonry walls.

The observed spalling or crushing in the areas supporting precast floor units occurred because concrete masonry units have much lower bearing strength than normal concrete members. Although not directly addressed in existing guidance, testing of precast ribs supported on masonry walls has confirmed increased spalling (Corney 2018). This suggests that seismic retrofit solutions designed to enhance the masonry wall supports to hollow-core floor units may need to be different from the solutions developed with concrete supporting members.

- **Irregularity effects**

The structural irregularity in buildings with hollow-core floors often caused significantly amplified seismic damage in some parts of the buildings and exacerbated damage not only in the lateral load resisting systems but also in the precast floors. In comparison, engineers commented that regular arrangements of lateral seismic resisting frames often resulted in much less damage to frames, although the damage to hollow-core floors sometimes was still significant because of the large building deflections caused by the high ductility used in design.

3 STRUCTURAL CHARACTERISTICS OF PRE-2006 CONCRETE BUILDINGS

To help inform the wider ReCast research programme, the structural characteristics of pre-2006 concrete buildings with hollow-core floors were categorised by searching and studying consent documents of buildings with hollow-core floors in Wellington. In total 165 existing concrete buildings with hollow-core floors were collated with the help from Wellington City Council (WCC) staff. The findings are summarised as follows:

- **Precast hollow-core floor systems and their support details**

The most common precast hollow-core floor systems used 200 series hollow-core units and had 50 mm to 70 mm concrete topping reinforced with cold-drawn mesh. Specified seating lengths of the hollow-core floor units varied greatly and they could be as small as 30 mm.

Starter bars were commonly grade 300 reinforcing bars of 12 mm in diameter, spaced at between 300 mm to 600 mm centre to centre. At the support ends of the hollow-core floor units, starter bars often stopped at a distance of 300 mm to 600 mm from the support edge.

Of significant concern is the uncertainty associated with hollow-core floors supported by concrete masonry walls as shown in Figure 1, which was observed in ~10% of the buildings surveyed. Masonry walls have significantly lower bearing capacities and lower stiffness and premature spalling of the masonry face shell supporting the hollow-core floor could easily occur.

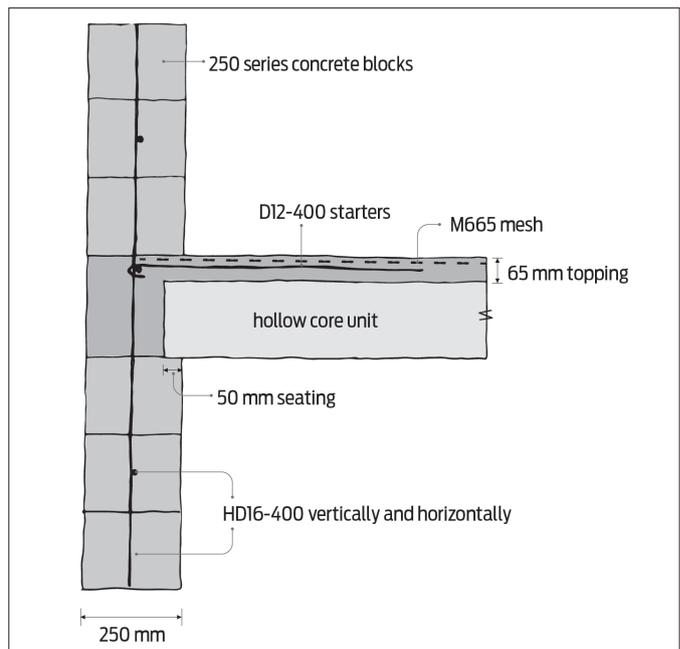


Figure 1: Concrete masonry walls supporting hollow-core floors

- **Pre-2006 concrete frame buildings**

For most pre-2006 reinforced concrete frame buildings, perimeter frames were seismic resisting systems and designed to a high ductility while internal frames were gravity load resisting systems, as shown in Figures 2 and 3. The different bay spacing between the gravity and seismic frames means that the two ends of a hollowcore unit supported at mid-span of a gravity frame and the plastic hinge zone of a perimeter seismic frame would experience differential rotations/movements. Such differential twisting in earthquakes would induce torsional responses, causing damage within individual hollowcore units or in the toppings.

In the case of a long narrow building subjected to shaking along the short direction, floor diaphragms need to bring the seismic actions from the floors to the lateral resisting systems spaced at a large distance. In such cases the floor diaphragms could be expected to have severe cracking in the floors, leading to large in-plane deflections as demonstrated in some earthquake damaged buildings in Wellington.

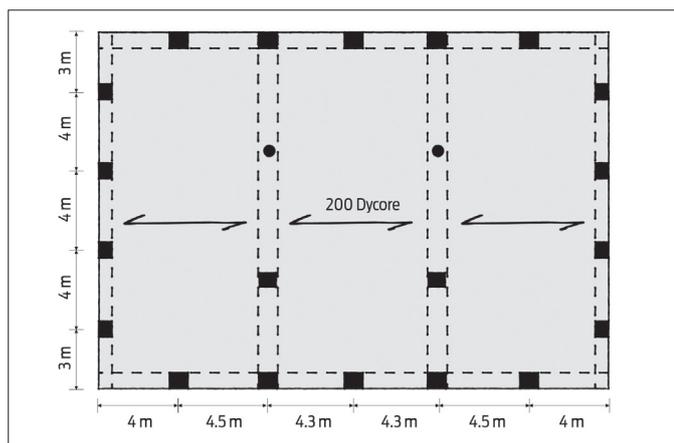


Figure 2: A typical floor plan of a 10-level building

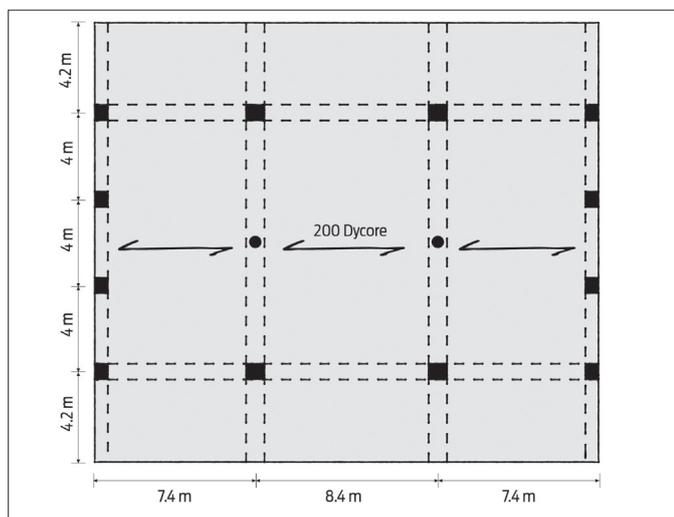


Figure 3: A typical floor plan of a 16-level building

- **Precast hollow-core units spanning multiple bays of moment resisting frames**

It was common in pre-2006 construction for hollow-core units to span parallel to two spans of moment resisting frames. This happens because the frame bay widths of seismic resisting frames along the perimeters are often much smaller than the spacing of internal gravity frames, as illustrated in Figure 2. The consequence is that hollow-core units need to accommodate the beam elongations from all the plastic hinges in the two frame spans. This significantly increases the deformation demands and risk of support loss in earthquakes and also exacerbates deformation incompatibility with the alpha slab adjacent to the frames (Fenwick et al. 2010).

- **No corner columns and structural irregularities**

It was not uncommon to find existing buildings that were designed as a ductile frame system with no corner columns, as shown in Figures 2 to 3. Such an arrangement potentially could substantially amplify the damage to the floors around the corners in earthquakes. If the building also has an irregular floor plan, for example, as shown in Figure 4, extra precautions need to be taken. This is because one end of the hollow-core units needs to be cut at an oblique angle to fit into the floor shape and, therefore, the construction tolerance at that end could compromise the seating length significantly. In other words, this structural irregularity would further increase the chance for support loss failure of some units adjacent to the corners.

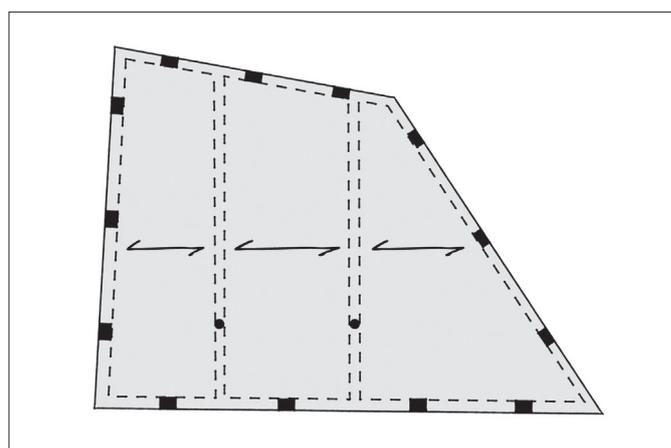


Figure 4: An irregular floor plan with no corner

4 SEISMIC RETROFIT OF EXISTING BUILDINGS WITH HOLLOW-CORE FLOORS

4.1 RETROFIT STATUS

Among the 165 existing buildings included in this study, 15 buildings had floor strengthening completed at the start of the ReCast program (2019), this representing less than 10% of them. Most of the floor strengthening was only in the form of providing supplementary floor unit seating by adding steel members (steel angles or steel hollow sections) 10 mm to 20 mm below the hollow-core floor soffit.

Clearly only a small portion of existing concrete buildings with hollow-core floors had been strengthened as of 2019 and concerningly there were many examples where seismic strengthening had been undertaken for the primary lateral load resisting systems without making effort to retrofit the hollow-core floors. For instance, many buildings with precast floors have undergone seismic strengthening by adding braced frames or walls but with no retrofits to address the floor vulnerabilities. The reason for the low strengthening efforts for the floors could be due to either of two reasons:

- Prior to 2010, no credible guidance documents for assessing and strengthening buildings with hollow-core floors were available, or

- After 2010, when relevant assessment guidance (Fenwick et al. 2010) was published, industry uptake of this guidance was slow.

4.2 RETROFIT METHODS

In general, currently used seismic retrofit solutions implemented in existing buildings with hollow-core floors could be classified into two broad categories: local behaviour improvement and global behaviour improvement.

Local behaviour improvement measures included enhancement of hollow-core floor seating by adding steel angles or steel hollow members either hard against floors or with a gap (10 mm to 20 mm) to the floors, as shown in Figure 5. It should be noted that testing by Liew (2004) and Parr (2019) showed that when stiffened angles or steel hollow members (e.g. SHS or RHS) are installed hard up against the soffit of the unit, that these retrofits can inadvertently trigger a negative moment failure in some cases. Additionally, it is acknowledged that many of the older seating retrofits do not provide an effective retrofit against positive moment failure (Brooke et al. 2022).

Additional local behaviour retrofits included adding catch frames for hollow-core alpha units (see Figure 6) and enhancing composite action for hollow-core alpha units by adding dowels (see Figure 7). In isolated cases seismic strengthening was undertaken after the Kaikōura earthquake due to the observed transverse cracks at

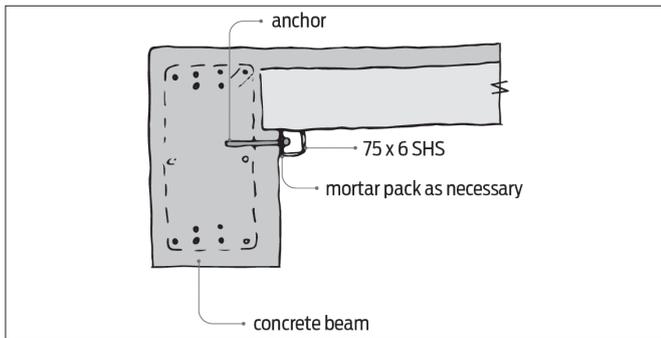


Figure 5: Supplementary seating

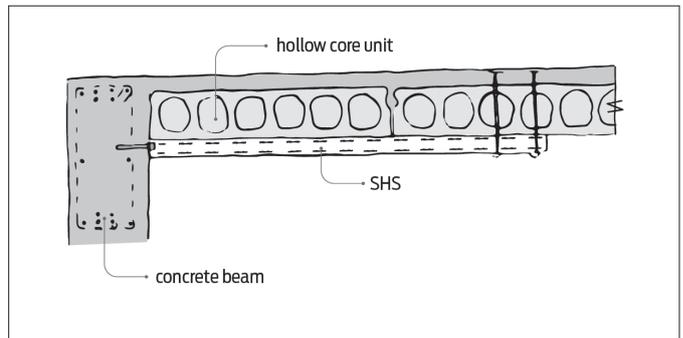


Figure 6: Catch frames to alpha units columns

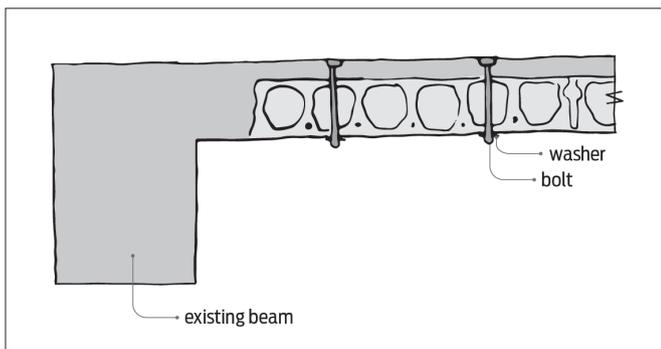


Figure 7: Ties through topping and units

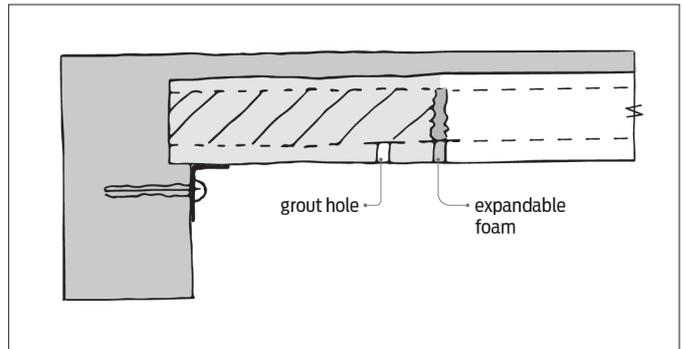


Figure 8: Grouting of hollow-core at supports

the bottom of the hollow-core floor units close to the supports. An example strengthening method is shown in Figure 8, where the hollow-core cells at their supports were grouted with no added reinforcement. The filling of cores has been recommended against since the publication of the document by Bull et al (Bull et al. 2009). Further discussion on the issues of filling cores as a retrofit or repair technique are described in the companion paper by Brooke et al. (2022).

Global behaviour improvement measures were designed to address the undesirable global performance issues such as unpredictable torsional issues in irregular structures, progressive failures caused by instabilities of corner columns or non-ductile gravity columns as well as inadequate diaphragm capacity of the floors. Examples of the global behaviour improvements included:

- Provision of new seismic resisting systems to reduce the lateral drifts or reduce torsional responses in irregular buildings;
- Addition of ties which restrain the perimeter columns into the floors;
- Provision of linkage from the internal gravity columns to the floor;
- Wrapping the non-ductile gravity columns using FRP (fibre-reinforced polymer);
- Provision of extra floor frame members in the cases of no corner columns;
- Enhancement of floor diaphragms by providing extra capacity based on analysis.

5 CONCLUSIONS

The real-world investigations formed an important research area of the ReCast project and the objective was to use real-world experience to help inform other research activities. The work reported in this paper was one element of the real-world investigations conducted to gain insights into the critical issues affecting the seismic performance of hollow-core floors. The issues studied included

- (1) Earthquake damage to existing buildings with hollow-core floors in the Kaikōura earthquake;
- (2) Engineering characteristics of pre-2006 buildings with hollow-core floors; and
- (3) Current strengthening status and retrofit solutions implemented for hollow-core floors.

With regard to earthquake damage vulnerabilities of hollow-core floors, the findings are that:

- Web cracking or splitting of hollow-core floor units may not be visible and different supporting systems at the two support ends of the hollow-core units may increase the likelihood of inducing web cracking/splitting.

- Spalling and loss of support would be more likely to occur if hollow-core floors are supported by reinforced concrete masonry walls. As such, retrofit solutions for hollow-core floors supported by block walls may need to be different from the solutions for reinforced concrete supporting members.
- Structural irregularities could significantly exacerbate earthquake damage around building corners.

As for engineering characteristics of pre-2006 frame buildings with hollow-core floors, the findings are that:

- It is common that perimeter frames of a concrete frame building were the lateral seismic resisting systems while internal frames were gravity resisting systems. As a result, the two ends of precast hollow-core floor units were supported by the structural systems of very different stiffness, potentially causing significant torsional response of the units in earthquakes.
- Hollow-core floor units often span parallel to two bays of lateral seismic resisting frames, thus increasing the deformation demands due to beam elongation and risk of support loss.
- Perimeter seismic resisting frames have no corner columns in many concrete frame structures.

As for the retrofit solutions used for hollow-core floors, the findings are that:

- Only a limited number of buildings in Wellington have received seismic strengthening due to the lack of technical retrofit guidance at the time of the investigation.
- The seismic retrofit methods used in strengthening the existing buildings with hollow-core floors have two broad categories: local behaviour improvement and global behaviour improvement.
- Local behaviour improvement solutions were primarily designed to address support loss of hollow-core units and prevent alpha units from collapsing. Retrofits for other failure modes had not been confirmed.
- Global behaviour improvement solutions varied significantly, including mitigating adverse effects related to some well-known structural behaviour at global performance level, such as high drift demands, torsional responses and progressive failures caused by column instability.

6 ACKNOWLEDGEMENTS

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