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Real world experience of seismic performance of buildings with hollowcore floors

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ABSTRACT

The cyclic test on a super-assembly of hollowcore floor and frames at the University of Canterbury around 2003 revealed the seismic vulnerability of hollowcore floor practice at that time. Subsequent tests were conducted to validate support details for improving seismic performance of hollowcore floors. Improved support details for hollowcore floors were introduced to NZS3101 in 2006.

Damage survey after Kaikoura earthquake confirmed the expected seismic vulnerabilities in pre-2006 precast hollowcore floors and it also revealed some previously unknown behaviour types. The Kaikoura earthquake provided significant impetus to advance our understanding of seismic performance of existing buildings with hollowcore floors. Subsequently, ReCast floors research programme was initiated. The programme has two streams: real-world investigations and lab-based investigations. The reported work is one component of real-world investigations. The objective is to obtain the information on observed earthquake damage patterns in Kaikoura earthquake, the engineering characteristics of existing Wellington buildings with hollowcore floors and currently used retrofit solutions in order to help inform ReCast research activities.

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1 INTRODUCTION

Concerns about the seismic integrity of precast concrete hollowcore floors constructed in New Zealand (NZ) were raised following the Northridge earthquake in 1994. As a result, the industry funded a research programme to investigate seismic behaviour of buildings with hollowcore floors constructed at that time.

One project of this industry-funded research programme was the simulated cyclic loading test on a full-scale super-assembly of hollowcore floors supported by frames, undertaken at the University of Canterbury, as shown in Figure 1 (Matthews 2004). The supporting details used in the test simulated the common practice before 2003. The test was performed using 300mm deep hollowcore floor system, which was an uncommon form of hollowcore floor systems. The test confirmed that hollowcore floors detailed at that time could be vulnerable in earthquakes and the observed evidence indicated serious gaps between assumed and actual behaviour of hollowcore floors in ductile frame buildings during strong earthquakes.

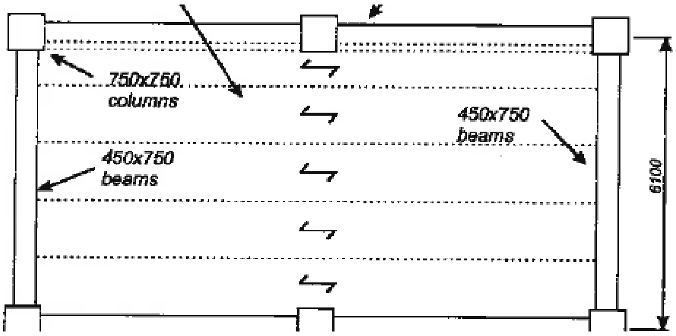

Figure 1: Layout of the super-assembly test (Matthews 2004)

Subsequently a series of super-assembly tests at system level (Lindsay 2004, Macpherson 2005) and tests on hollowcore units at component level (Jensen 2006, Woods 2008) were undertaken to validate the support details of hollowcore units to improve their seismic performance in new buildings. The validated support details for hollowcore floors were introduced to NZS3101 in 2006 (SNZ 2006).

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

Earthquake damage survey from TAP programme revealed that hollowcore floors were very vulnerable in earthquakes, compared with other precast floor systems. The work within TAP confirmed the seismic vulnerabilities of pre-2006 precast hollowcore floors as revealed in Matthews's test and it also revealed some previously unknown behaviour types (Henry 2017). This brought about the realization that the reasonably modern buildings with hollowcore floors constructed before 2006 could have significant damage and/or collapse in design earthquakes and potentially become the new class of vulnerable buildings in earthquakes.

Assessing the likely performance of pre-2006 precast floors presented a significant challenge for engineers. MBIE established a working group after Kaikoura earthquake and drafted a guidance document on assessment of precast floors for engineers to use in the short term. This guidance document was produced, mainly based on a past research summary document produced at the University of Canterbury (Fenwick 2010) and it was added, for the first time, to the technical guidelines for engineering assessments "the seismic assessment of existing buildings" in 2017 (NZSEE et al 2018). However, many questions remain unanswered about assessment of precast floors as revealed from the observed earthquake damage (Henry 2017) and further research is urgently needed to improve the guideline. Engineers will also urgently need direction on validated retrofit approach to address the identified vulnerable buildings with precast floors. As such, the ReCast research programme was initiated (Brooke 2019) and the programme has two streams: real-world investigations and lab-based investigations. The work reported here is part of real-world investigations of ReCast programme and the objective was to use real-world experiences to help inform the research.

2 ABOUT THE REAL-WORLD INVESTIGATION IN THIS STUDY

Floors are integral parts of a building structure and they play significant roles to ensure the buildings to remain standing in different loading conditions. In a gravity loading condition, the floors bring the gravity loads from floors to the supporting members and meanwhile act as lateral restraining members to ensure stability of vertical gravity load carrying systems, such as, columns and walls. In earthquakes, the floors also act as diaphragms to transfer the seismic actions across the buildings to lateral load resisting systems below. As such, floors can be subjected to significant direct and indirect seismic actions. Direct actions are results of the loads on floors, and indirect actions are results of deformation incompatibility between the supporting systems and the floors. The latter presents a great challenge for buildings with precast hollowcore floors.

Hollowcore floors consist of precast hollowcore floor units and thin in-situ reinforced concrete topping. Although precast hollowcore floor units are one-way spanning elements between supporting members, precast floor systems are two-way systems in order to transfer seismic actions across the buildings in earthquakes. The two-way behaviour of the floors is achieved by the thin in-situ reinforced concrete topping slabs, where short starter bars are usually provided from the topping to the supporting members along the edges of the floors, creating some degrees of continuity along the slab edges.

There are many potential issues for hollowcore floor systems. At first, there are significant deformation incompatibility issues between one-way spanning hollowcore units and the two-way functioning in-situ topping slabs, and this will induce shear actions between hollowcore units as well as between hollowcore units and in-situ slabs. At the supports of hollowcore units, the seismic behaviour of floor systems is likely to have negative moment failure if the starter bars are short. This creates significant uncertainties of the potential seismic responses of the floors as well as the entire buildings. In detail, the actions introduced to the floors could cause the floors to fail or be damaged locally. The local failure/damage of the floor systems could result in the loss of the lateral restraints to gravity supporting systems, leading to the instability of the primary supporting systems and progressive failure/ collapse of the entire building. As such, the buildings with hollowcore floors do not have the same integrity as the buildings with in-situ floor systems.

Great research efforts, although limited, have been made at the University of Canterbury and the University of Auckland on studying seismic behaviour of hollowcore floors. Many different failure modes, such as, positive moment failure, negative moment failure and loss of support, have been identified in the past (PCFOG 2009, Fenwick 2010). ReCast programme was established in 2018 to study the unknown seismic behaviour of hollowcore floors revealed in recent earthquakes and to develop effective retrofit solutions needed to help achieve seismic resilience of this class of buildings.

The real-world experience reported in this paper was designed to help ensure the ReCast research efforts to be relevant to the real-world situations and it contains three research tasks described as follows:

- To use the real-world experiences in Kaikoura earthquake to help characterise the failure modes of hollowcore floors in earthquake, which requires further investigations;
- To gain insights into the engineering characteristics of existing buildings with hollowcore floors in order to help inform the lab-based research and theoretical simulations; and
- To gain insights into currently used retrofit solutions associated with hollowcore floors.

3 CHARACTERISTICS OF EARTHQUAKE DAMAGE

3.1 General

A huge engineering effort was made in the TAP programme in assessing seismic damage of the existing buildings with hollowcore floors in Wellington. The work within TAP programme had lots of valuable information. However, researchers have no way to get access to the damage assessment reports of the buildings in the TAP programme, due to the confidentiality issues or other issues (insurance claims so on). Surveying earthquake damage in buildings of interests was extremely difficult because of many concerns including health and safety concern. As such, the intended effort for conducting the real-world investigations into Wellington buildings with hollowcore floors had many challenges.

In order to characterise the earthquake damage patterns observed in hollowcore floors at component level and global performance level, input was sought from engineers, who had real-world experiences in evaluating buildings with hollowcore floors after Kaikoura earthquake. Input was also sought from contractors, who were involved in demolishing or strengthening buildings with hollowcore floors. As such, the engineering professionals provided insights into damage patterns in hollowcore floors and insights into the effects of global structural characteristics of a building on seismic damage in hollowcore floors, which are not easy to obtain from the lab testing.

3.2 Characteristics of damage observation in hollowcore floors

Most of the damage patterns discussed with the engineers were covered in the report by Henry et al (Henry 2017). Apart from the damage patterns summarised by Henry, the engineers and contractors also highlighted other damage characteristics as described as follows:

- Hidden web cracking and/or splitting of hollowcore floors

Web cracking and web splitting could be invisible. In a few buildings with no visible damage to hollowcore units, engineers confirmed web cracking/splitting by conducting investigations using borescope cameras.

- Web cracking/splitting versus the incompatibility of the supporting systems

A commonly reported phenomenon was that the revealed web cracking/web splitting was often associated with incompatible supporting systems at two ends of hollowcore units. For instance, hollowcore units 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 ends of hollowcore units introduced torsion to the units, causing the damage to hollowcore webs.

- Vulnerability of reinforced concrete block wall

Damage to reinforced concrete block walls in a mainly reinforced concrete frame building was very severe, the damage included spalling/crushing of the reinforced concrete block walls in the areas supporting the floor unit, and severe diagonal shear cracking to the block walls.

The observed spalling or crushing in the areas supporting precast floor units occurred because concrete block work has much lower bearing strengths than normal concrete members. This suggests that seismic retrofit solutions designed to enhance the block wall supports to hollowcore floor units could be different from the solutions developed with concrete supporting members. The observed diagonal cracks in block walls could be the result of progressive failure in a building structure with incompatible lateral load resisting systems. If a reinforced concrete frame structure has mixed lateral seismic resisting systems including concrete frames and block walls, the building will attract higher seismic actions than its frame counterpart in earthquakes. The block walls will resist a great deal of seismic actions until they get damaged, then the concrete frames are mobilised, and the seismic performance behave similar to a bare frame structure. This is a typical progressive failure scenario.

- Irregularity effects

The structural irregularity in a building with hollowcore floors often caused significantly amplified seismic damage in some parts of the buildings and the exacerbated damage was observed not only in the lateral load resisting systems but also in the precast floors. In comparison, the engineers commented that regular arrangements of lateral seismic resisting frames often resulted in much less damage to frames, although the damage to hollowcore floors sometimes was still significant because the buildings often deflected a lot in earthquakes due to the ductile design philosophy used in original designs.

4 STRUCTURAL CHARACTERISTICS OF PRE-2006 FRAME BUILDINGS

To help inform the wide ReCast research, the structural characteristics of pre-2006 concrete frame buildings with hollowcore floors were categorised by searching and studying consent documents of some buildings with hollowcore floors in Wellington. The findings are as follows:

- Precast hollowcore floor systems and their support details

The most common precast hollowcore floor systems used 200 series hollowocore units and had 50 mm to 70 mm concrete topping reinforced with cold-drawn mesh. Specified seating lengths of the hollowcore floor units were varying and they could be as small as only 30 mm. Starter bars at the ends of the hollowcore floors units often stopped at a distance of 300 mm to 600 mm from the support edge and they were commonly 300 MPa 12 mm in diameter bars spaced at 300 mm to 600 mm centre to centre.

- Primary structural systems of pre-2006 concrete frame buildings

For most of pre-2006 reinforced concrete frame buildings, perimeter frames were seismic resisting systems designed to a high ductility while internal frames were gravity load carrying systems, as shown in Figure 2 and Figure 3. When the buildings have the perimeter frames as the only seismic resisting systems, the systems would have the maximum torsional resistance, which is an advantage. However, there are implications, in terms of the expected seismic performance of the floors.

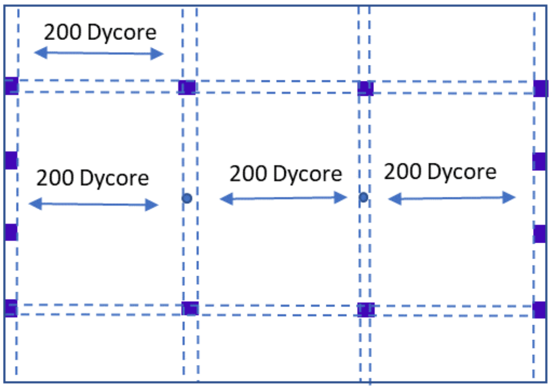

Figure 2: A typical floor plan (a 10-level building)

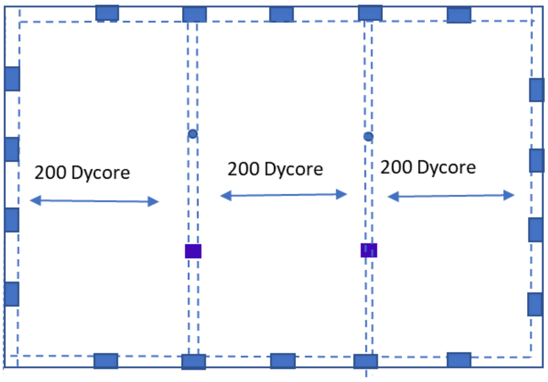

Figure 3: A typical floor plan (a 16-level building)

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 and the floor diaphragms could be expected to have severe cracking in the floors, leading to large in-plane deflections, as demonstrated in some buildings in Wellington. In the case of concrete frame buildings being not narrow, it was very common that the hollowcore floor units were supported by perimeter seismic resisting frame at one end but by internal gravity frame at the other end, as shown in Figure 2 and Figure 3. The result is that differential movements at two ends of the hollowcore units in earthquakes would induce torsional responses and cause damage within individual units or in the toppings.

- Precast hollowcore units spanning over multi-spans of lateral seismic resisting frames

It was common in pre 2006 construction that hollowcore units span parallel to two spans of moment resisting frames. This happens because the frame spans of seismic resisting frames along the perimeters are often much smaller than the spacing of internal gravity frames, as illustrated in Figure 3. The consequence is that hollowcore units need to accommodate the beam elongations over all the plastic hinges in the two frame spans, significantly increasing the chances of the floor units coming off the supports in earthquakes.

- No corner columns and structural irregularity effect

It was not uncommon to find that an existing building was designed as a ductile frame system with no corner columns present, as shown in Figures 2 to 4. Such an arrangement potentially could amplify the damage to the floors around the corners in earthquakes a lot. If the building also has an irregular floor shape as shown in Figure 4, extra cautions need to be taken. This is because the initial installation of hollowcore floor units was likely to have short seating problem and the structural irregularity would further increase the chance for some units around the corners to come off the supports. The columns adjacent to the corners then could lose stability, triggering the progressive failure of the building.

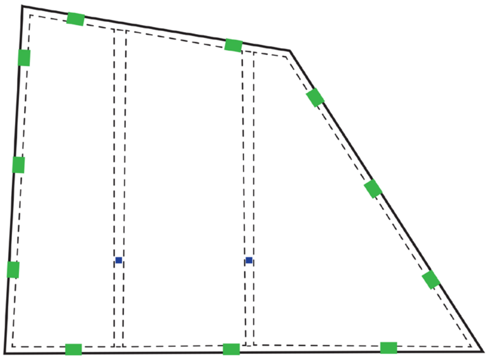

Figure 4: A typical floor with no corner columns

5 CURRENT SEISMIC RETROFIT METHODS

Limited consent documentation search has found that only a small number of the existing buildings with hollowcore floors were seismically strengthened. The reason could be because no credible guidance documents for assessing and strengthening buildings with hollowcore floors currently are available. In general, currently used seismic retrofit solutions in existing buildings with hollowcore floors could be classified into two broad categories: local behaviour improvement and global behaviour improvement.

Local behaviour improvement measures included enhancement of hollowcore floor seating by adding steel angles or steel hollow members either hard against floors or with a gap (10 mm to 20 mm) with the floors (as shown in Figure 5); adding catch frames for hollowcore Alpha units (Figure 6), enhancing composite action for hollowcore Alpha units between topping and precast hollowcore floor units for by adding ties (Figure 7). In isolated cases, seismic strengthening was undertaken, after Kaikoura earthquake, due to the observed transverse cracks at the bottom of the hollowcore floor units close to the supports. An example strengthening method was shown in Figure 8 where the hollowcore cells at supports were grouted with no added reinforcement. The benefit of this type of strengthening is not very clear.

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 diaphragm capacity of the floors. Examples of the global behaviour improvements included the follows:

- Provision of new seismic resisting systems to reduce the seismic deflection or reduce torsional responses in an irregular building structure;
- Addition of ties which tie the perimeter columns, especially corner columns into the floors using Reidbar braces or similar
- Provision of linkage from the internal gravity columns to the floor
- Wrapping the non-ductile gravity columns by FRP (fiber-reinforced polymer)
- Provision of extra floor frame members in the cases of no corner columns
- Enhancement of floor diaphragms by providing extra capacities wherever analyses show inadequate

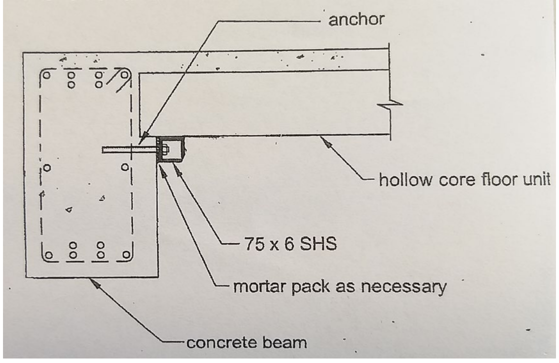

Figure 5: Adding seating to hollowcore units

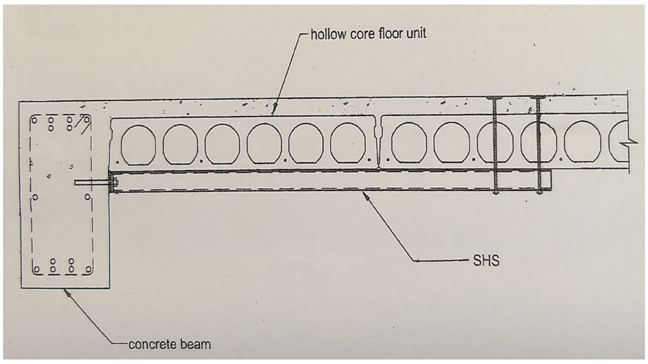

Figure 6: Adding catch frames to alpha units

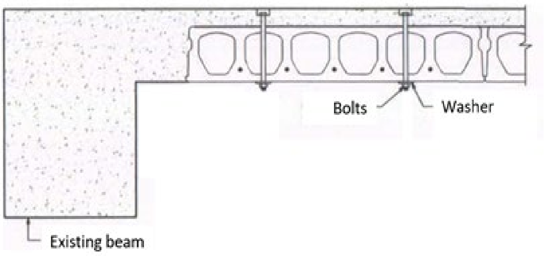

Figure 7: Adding ties from topping to the units

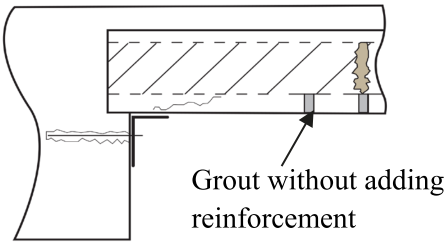

Figure 8: Grouting of hollowcore cells at the support

6 CONCLUSIONS

One important research area of the research programme “ReCast” on seismic behaviour and retrofit of buildings with hollowcore floors is the real-world investigations and the objective was to use real-world experiences to inform other ReCast research activities. The work reported in this paper was one element of the real-world investigations within ReCast and it was to gain the insights into the critical issues affecting seismic performance of hollowcore floors. The issues studied included (1).Earthquake damage vulnerabilities of existing buildings with hollowcore floors in Kaikoura earthquake; (2). Engineering characteristics of pre-2006 buildings with hollowocore floors; and (3). Currently used retrofit solutions for hollowcore floors.

With regard to earthqauke damage vulnerabilities of hollowcore floors, the finding are:

- Web cracking or splitting of hollowcore floor units could be invisible and different supporting systems at the two ends of the hollowcore units would make the web cracking/splitting more likely to occur.
- Spalling and then loss of support would be more likely to occur if hollowcore floors are supported by reinforced concrete block masonry in a mainly concrete frame building. As such, retrofit solutions for hollowcore floors supported by block walls could be different from the solutions for concrete situations.
- Structural irregularities could exacerbate earthquake damage around building corners significantly.

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

- It is common that perimeter frames are the only lateral seismic resisting systems while the internal frames are gravity frames. As a result, the two ends of precast hollowcore floor units were often supported by the structural systems of very different stiffness behaviour, potentially causing significant twist actions in the floor units in earthquakes.
- Hollowcore floor units often span parallel to two frame spans of lateral seismic resisting frames, thus increasing the possibility for the hollowcore units to come off the seating because of increased beam elongation.
- Perimeter seismic resisting frames have no corner columns in many concrete frame structures.

About currently used retrofit solutions for hollowcore floors, the findings are:

- There are only limited seismic strengthening activities due to the lack of technical guidance.
- The current seismic retrofit methods used in strengthening the existing buildings with hollowcore floors have two broad categories: local behaviour improvement and global behaviour improvement.
- Local behaviour improvement solutions were designed to address loss of support for hollowcore units and prevent alpha units from collapsing. No retrofit had been devised to address other failure modes.
- Global behaviour improvement solutions varied significantly, including mitigating adverse effects related to some well-known structural behaviour at global performance level, such as, torsional responses, progressive failures caused by instabilities of corner columns or gravity columns, so on.

ACKNOWLEDGEMENTS

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