

Seismic Performance of Precast Hollow-core Units Seated Within the Plastic Hinge Region

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ABSTRACT

This paper discusses the susceptibility of hollow-core floor units to sustain a higher degree of damage when they are seated within the plastic hinge regions of the supporting beam. This damageability of these so-called ‘beta units’ is neither recognised in the current design standard, NZS3101:2006-A3, nor in the technical proposal aiming to revise the Assessment Guidelines C5. This poor seismic performance of beta units has been recently identified from observations of a case study building damaged during the 2016 Kaikōura Earthquake, as well as from two full-scale hollow-core floor tests subjected to bi-directional drift demands. The seismic performance of beta units from both the case study building and the floor test are summarised in this paper. It was found that beta units sustained damage at low drift levels and incurred overall more damage than units that were seated outside the plastic hinge zone. Observations from both the test and the case study building suggest that beta unit damage is sensitive to the boundary conditions of the unit, bending demands in the transverse and longitudinal direction of the unit, as well as inertial diaphragm forces.

1 INTRODUCTION

Following the collapse of precast hollow-core floors during the 1994 Northridge earthquake in California, post-earthquake reconnaissance revealed critical shortcomings of the support connection detailing (Norton et al., 1994). These floor collapses raised serious concerns regarding the expected seismic performance of precast hollow-core floors in New Zealand where design and detailing requirements were largely similar to US practice. Particularly with hollow-core floors being the most ubiquitous flooring system in New Zealand’s multi-storey buildings stock (Park, 1995; International Federation for Structural Concrete, 2003; Puranam et

al., 2019). Given the prevalence of hollow-core flooring in New Zealand cities, a series of experiments into the seismic response of hollow-core floors and the improvement of their seismic performance has been undertaken over the past three decades in New Zealand (Mejia-McMaster, 1994; Oliver, 1998; Herlihy, 1999; Liew, 2004; Matthews, 2004; Lindsay, 2004; MacPherson, 2005; Jensen, 2006; Woods, 2008; Corney, 2018). This previous research led to three key outcomes:

- Identification of three primary failure mechanisms that could occur in existing precast hollow-core units under seismic demands, namely loss of support, negative moment failure and positive moment failure (Fenwick et al., 2010).
- Quantification of the lateral drift that can cause each of the failure mechanism identified (i.e. the assessment of hollow-core units seismic capacity) as described by Fenwick et al. (2010) and further refined in the New Zealand Seismic Assessment Guidelines (MBIE et al., 2018).
- Development of improved floor-to-support connection detailing for new construction achieving enhanced seismic performance, which is currently incorporated in the concrete design standard, NZS3101:2006-A3 (Standards New Zealand, 2017).

Although previous research has substantially contributed to understanding the seismic performance of precast hollow-core floors, damage observations of hollow-core floors following the 2016 Kaikōura earthquake showed unexpectedly poor performance of floors incorporating up-to-date detailing. In particular, it stood out that most of the concerning damage occurred to units seated at or adjacent to an intermediate column (within the plastic hinge regions of the supporting beams). The damage patterns observed in units seated at the intermediate columns were notably inconsistent with the previously identified failure mechanisms.

Hollow-core units seated within the plastic hinge region of the support beam can generally be classified into two primary categories. Namely, units that are immediately adjacent to a parallel moment frame beam (usually referred to as 'alpha' units within the structural engineering community in New Zealand) and units that are supported at or adjacent to an intermediate column (referred to as 'beta' units in this paper) (Figure 1).

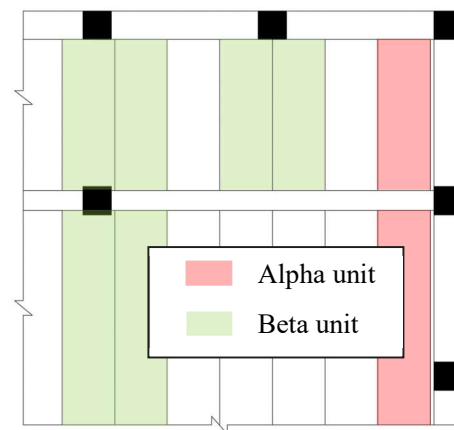


Figure 1: Schematic highlighting the difference between 'alpha' and 'beta' units

The susceptibility of 'alpha' units to sustain severe earthquake damage has been recognised since the early 2000's after the full-scale super-assembly test on hollow-core floors conducted by Matthews (2004). Matthews highlighted the vulnerability of hollow-core units in general and investigated the potential damaging mechanisms associated with alpha units. The damageability of 'beta' units, however, has not been previously considered in any research studies. Beta units' seismic performance and potential damaging mechanisms are

notably not addressed at any rate in the New Zealand concrete design standard, NZS3101:2006-A3, or in the current seismic assessment guidelines - C5 (MBIE et al., 2018).

This paper highlights the susceptibility of beta units to sustain severe damage and summarises damage observations of beta units from a case study building that sustained earthquake damage during the 2016 Kaikōura earthquake and two full-scale super-assembly tests. Detailed damage inspection of hollow-core floors, incorporating up-to-date detailing requirements, was undertaken in the case study building. Correlation between damage severity and the hollow-core unit locations relative to the plastic hinge region has been derived by analyses of field data. Furthermore, super-assembly testing incorporating beta units with common 1980s detailing was conducted and key damage trends are presented. The observations from both the field investigation and the super-assembly tests are discussed, along with concerns regarding potential implications these observations have on the current concrete design standard, NZS3101:2006-A3, and the relevant seismic assessment guideline - C5 (MBIE et al., 2018).

2 PERFORMANCE OF HOLLOW-CORE UNITS SEATED WITHIN THE PLASTIC HINGE REGION

Extensive research investigating the seismic performance of precast hollow-core floors has been undertaken over the past 25 years in New Zealand, as summarized in Corney et al. (2021). Most of the research conducted on the seismic performance of hollow-core floors was focused on how hollow-core floors can cope with relative rotation of the supporting beam and elongation due to plastic hinging of the beams which run parallel to the precast unit, as shown in Figure 2a. However, there has been no research investigating the performance of hollow-core floors subjected to deformations of the supporting system transverse to the floor span direction, as depicted in Figure 2b. These transverse deformations of the support structure can induce significant bending and twisting into the flooring unit along its longitudinal axis.

Beta units, as per previous definition are located at or next to intermediate columns and therefore, are subjected to the transverse deformations of the support structure (Figure 2b), in addition to demands in the longitudinal direction (Figure 2a).

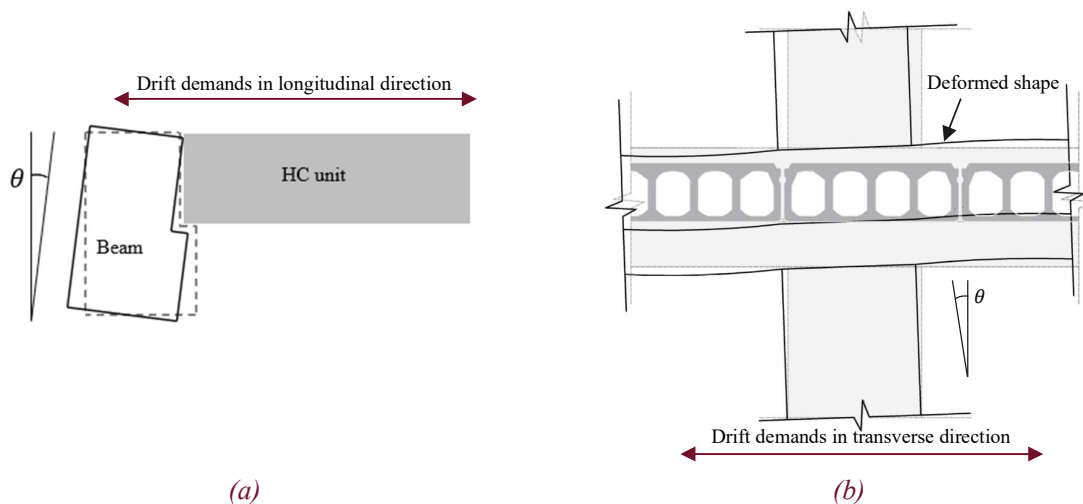


Figure 2: a) deformations caused by rotation of support beam in the longitudinal direction of the unit b) deformations caused by rotation of support beam in the transverse direction of the unit

2.1 Boundary Conditions

The support boundary conditions are expected to significantly affect the performance of beta units. Different boundary conditions can directly impact the expected behaviour and severity of damage to beta units.

Generally, beta units can be classified as follows:

1. A hollow-core unit with its centreline located within column width (Figure 3a).
2. A hollow-core unit with its centreline located within the plastic hinge region (Figure 3b). The plastic hinge length in this application was taken as half of the supporting beam depth.

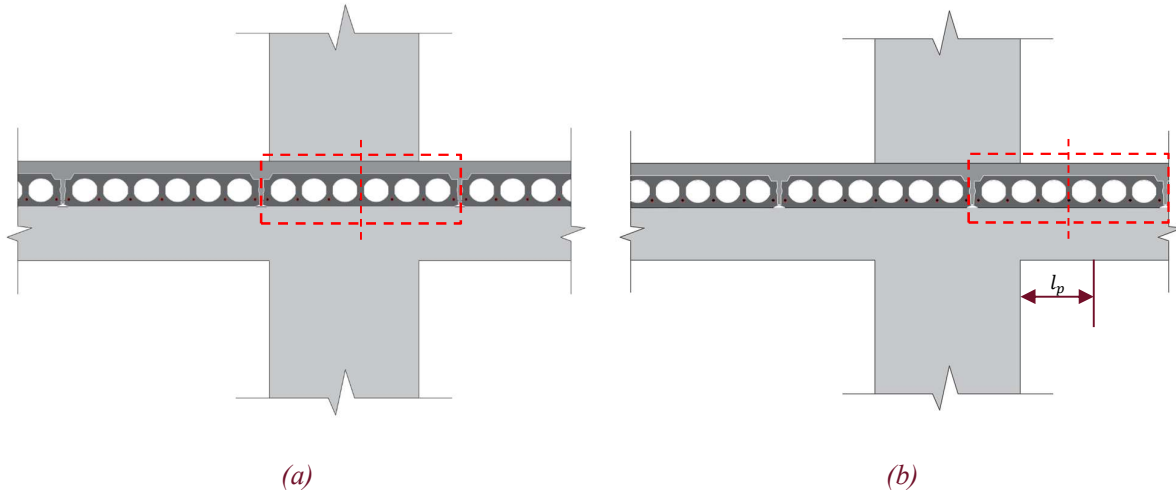
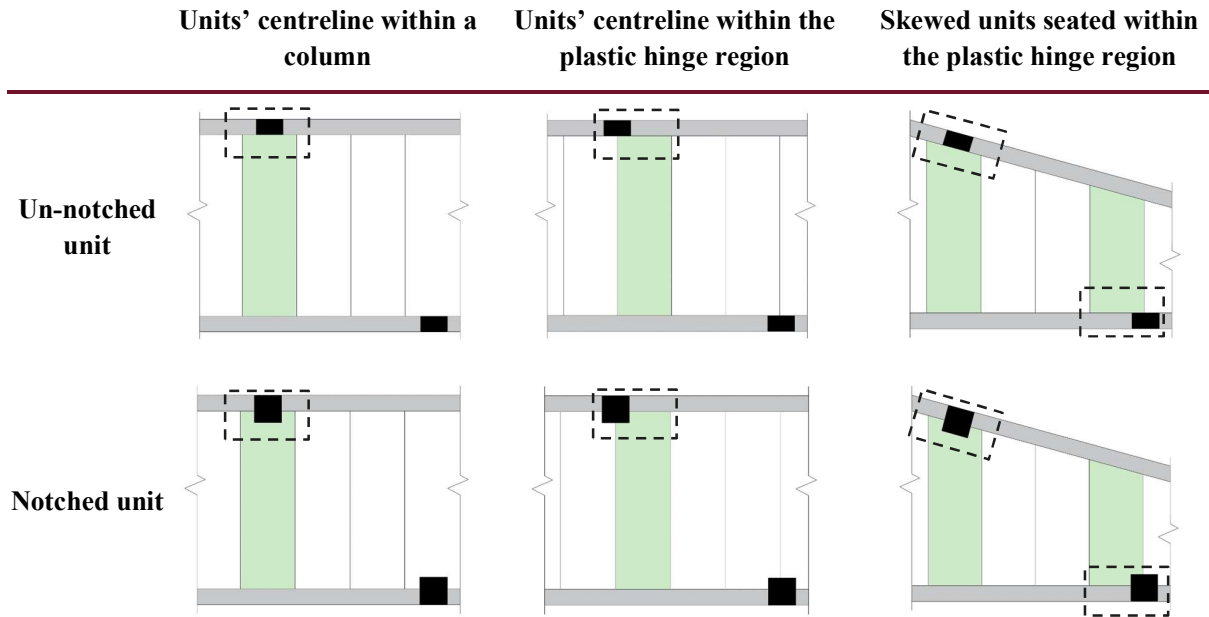


Figure 3: Schematic of beta units classification a) unit centreline within column width b) unit centreline within plastic hinge region

Units seated across the beam-column interface can experience substantial deformations due to minor hinging or even under elastic deformation of the supporting beams. Moreover, in many cases, beta units are notched to account for the column geometry. This notch will cause a concentration of stresses making these units more vulnerable to sustain damage under seismic demands. These boundary conditions make these units more prone to sustain damage in the unreinforced webs of those beta units at relatively low drift levels.

A summary of possible boundary conditions is schematically illustrated in Table 1 can be used to classify beta units.

Table 1: Schematic of different possible boundary conditions of beta units



2.2 Recent Observations

2.2.1 Field Observations

Observations from an instrumented building with hollow-core floors following the 2016 Kaikōura earthquake showed unexpectedly poor performance of beta units. The beta units in the building discussed herein can be classified as un-notched units, and the centreline of the units was either within the column width or the plastic hinge region. The floor-to-support connection detailing used in the building investigated incorporated the detailing requirements of the current design standard, NZS3101:2006-A3. However, beta units were observed to incur more damage than units seated away from the plastic hinge regions and severe damage to beta units due to other mechanisms was observed (Figure 4).



Figure 4: Examples of beta units damage observed a) previously unidentified damage pattern b) transverse cracking at the unit soffit accompanied by longitudinal cracking

To quantify the extent of damage sustained in the floors, a qualitative framework was developed to classify different observed damage states. The inspection of the floor units was only possible from the soffit. Hence the categorisations of the damage sustained in the hollow-core units primarily relied on the inspection of the floor unit's soffit. Each unit end was assigned a damage state from light-severe based upon how likely the gravity load path was compromised. A light damage state represented negligible or cosmetic damage, and a severe damage indicated that the unit would likely collapse when subjected to design gravity loads. The damage severity for each end of the hollow-core units was plotted against each unit location relative to the nearest column for 684 unit-ends (i.e. 342 units), as shown in Figure 6. It was noted that there was a trend for the damage severity, where the closer the unit was to a column, the higher the degree of damage. Furthermore, beta units were observed to sustain transverse cracking at the unit soffit accompanied by web cracking (Figure 5) at storey drift demands as low as 0.6% in the longitudinal direction of the unit and 1.0% in the transverse direction. More severe beta units damage was sustained at higher drift demands. Preliminary analysis suggests that diaphragm demands exacerbate the damage to beta units due to the tendency of collector forces to concentrate at column locations. These inertial loads increase up the height of the building due to higher floor accelerations may have influenced the occurrence of beta unit damage at the low drift demands experienced by the upper floors of the case study building (Mostafa et al., 2022).



Figure 5: Damage sustained in hollow-core unit under low drift levels

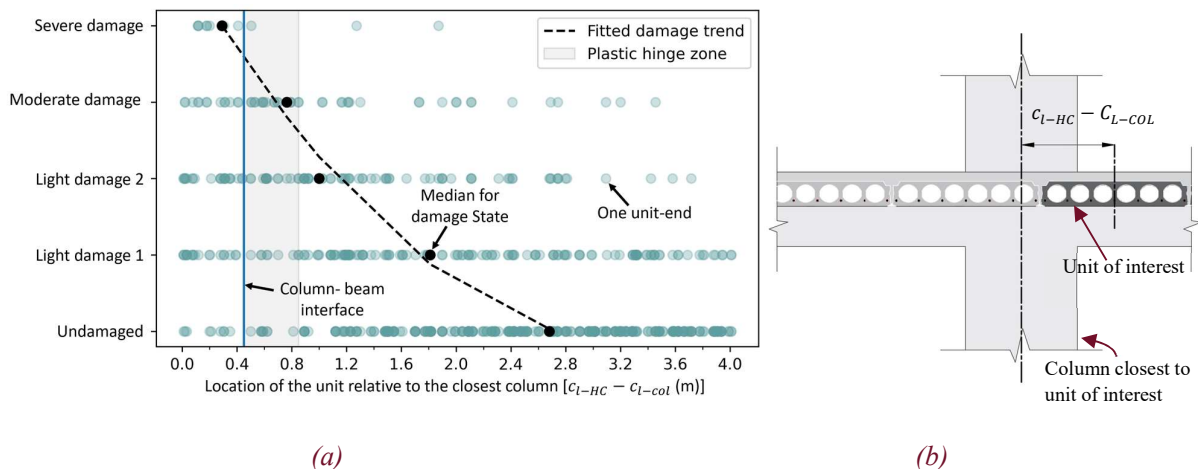


Figure 6: a) damage trend observed in the case study building showing the closer a unit is to the column the higher degree of damage b) schematic showing location definition for units used in the damage trend plot

2.2.2 Super-assembly tests

Besides the evidence of beta unit damage observed in the field, recent laboratory testing revealed further insights into the fragility of beta units. Two full-scale super-assembly specimens representing part of a lower storey in a typical ductile RC frame building with hollow-core floors were tested in the laboratory facilities at the University of Canterbury.

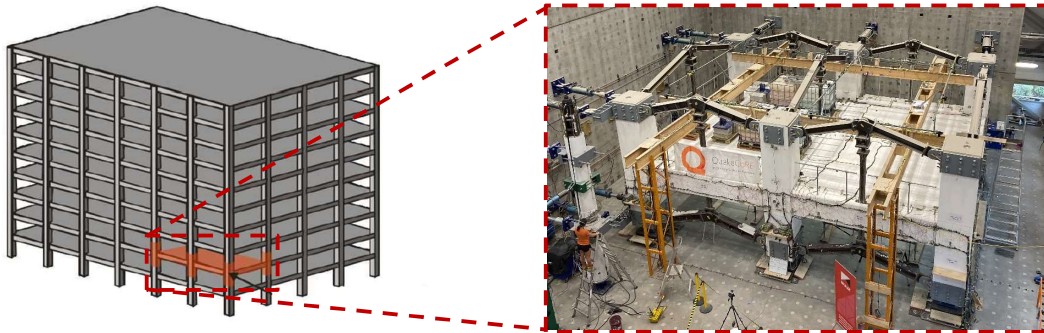


Figure 7: Schematic showing full-scale test concept, prototype building figure is modified from (Woods, 2008)

The connection detailing and layout of the tested single span hollow-core floor is representative of existing 1980s buildings in Wellington (Figure 8a). The specimen comprised two beta units with notches to fit the units around the precast columns as shown in Figure 8b.

While those two beta units were not seated on the column directly, a connection through the column ties that extended from the middle columns into the topping layer existed.

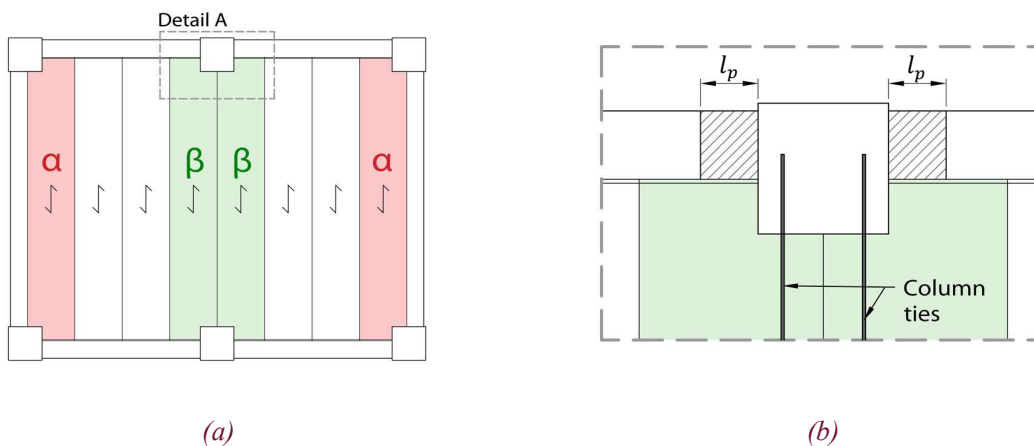


Figure 8 - Super-assembly specimen showing (a) top view of the beta unit seating arrangement and (b) Detail A of beta unit support

As the experiments progressed, local deformation induced into the beta units caused external floor damage in the form of transverse, diagonal and longitudinal cracking in the vicinity of the notches (Figure 9a). This region of high discontinuity in the beta units appeared to be more prone to damage compared to the support region of hollow-core units that are seated away from the plastic hinges.

Moreover, the onset and extent of internal cracking of the unreinforced webs in beta units was more substantial compared to other units seated away from the plastic hinges, but not as severe as in alpha units. An example of a web-crack in the direction of gravity shear in a beta unit is shown in Figure 9b.

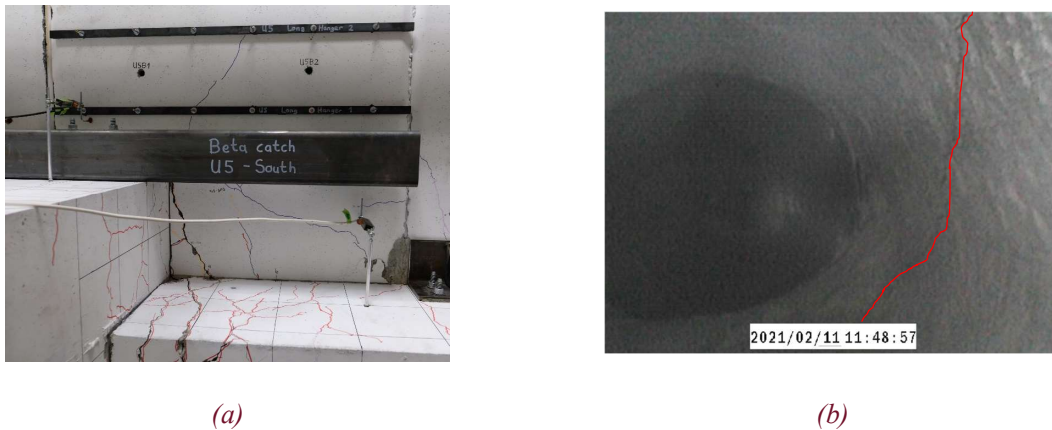


Figure 9: Examples of beta unit damage showing (a) soffit cracking in beta unit at 2.5% in Test 1 and (b) web-crack in beta unit at 1.0% drift in Test 2 as seen from unit void (highlighted in red)

The two super-assembly experiments also furthered the understanding of how elongation from plastic hinges at intermediate columns can impact the floor diaphragm of a typical existing hollow-core floors. In the first test, the elongation of the plastic hinges at the intermediate columns generated a full-length longitudinal split between the beta units as shown in Figure 10a. Once the non-ductile 665 HRC mesh across the split ruptured, all the deformations concentrated in this single crack, resulting in a complete separation of the floor diaphragm. While inertial forces were not simulated in the super-assembly tests, such beta unit damage is expected impact the diaphragm load paths significantly.

In terms of beta unit performance, the longitudinal split reduces the demands induced into the beta units themselves due to transverse deformations. This is because the split relieves the restraint from the neighbouring beta unit. On the contrary, the split also removed any gravity load sharing between the already heavily damaged beta units.

It is worth noting that, in the second test, the column ties were post-installed with additional transverse stitching bars to replace the load path across the cut mesh. The presence of the ductile stitching bars did hinder the crack to form between the beta units but caused the longitudinal split to form beyond these bars through the beta unit itself, as shown in Figure 10b.



(a)



(b)

Figure 10: Longitudinal splitting from elongation of plastic hinges at intermediate columns forming (a) between the beta units and (b) beyond the stitching bars within the beta unit (highlighted in green).

More specific information about the super-assembly test in regards of the specimen details, loading and floor damage progression can be found in (Büker et al., 2022).

3 CONCERNS

The damage observations presented in this paper show clear evidence that beta units are susceptible to sustaining a more significant degree of damage relative to other (non-alpha) units and, depending on the boundary conditions, critical damage during earthquake loading. From the observations discussed herein, the following concerns arose:

- The susceptibility of beta units to sustain a higher degree of damage compared to other units, as observed in the case-study building, is not recognised in the current concrete design standard, NZS3101:2006-A3. Furthermore, beta units were found to receive critical damage, unreinforced web-cracking, that potentially impairs the gravity load-carrying capacity during and after an earthquake, even with inter-storey drift demands lower than 2.5% (Ultimate limit state design drift limit). Based on these findings, the code conformity of the current support detailing for beta units has been drawn into question (SESOC et al., 2021).
- The damageability of beta units is not addressed in the most up-to-date draft of the New Zealand seismic assessment guidelines for hollow-core floors (MBIE et al., 2018). Not addressing the vulnerability of beta units in the assessment guidelines has two adverse consequences:
 - A critical beta unit may remain un-retrofitted,
 - The design and detailing of the retrofit may not fully address the expected beta unit damage.
- Beta units play an important role in the diaphragm resistance due to their location close to columns. The interaction between beta unit damage and the diaphragm is complex. On one hand, diaphragm actions can induce additional unintended tension forces into beta units, causing critical damage to these units (e.g. beta unit damage influenced by diaphragm actions shown in Figure 5). On the other hand, damage sustained by beta units can significantly impair the diaphragm load paths (e.g. full-length longitudinal splitting between beta units observed in super-assembly test shown in Figure 10).

- The damage observations presented in this paper come from highly regular floor layouts. Irregular floor layouts with different boundary conditions at each end are expected to exacerbate the fragility of beta units damage (e.g. additional torsion demands).

4 FUTURE WORK

Currently, more detailed forensic work on the beta unit damage that was observed in the case study building and the super-assembly tests is underway. The aim of this work is to relate the imposed local deformation to the recorded damage patterns in the beta units. This work will yield an improved understanding of the causes for specific beta unit damage patterns with respect to the unit's support boundary conditions.

Furthermore, as the design of hollow-core units to resist gravity loads in shear assumes an uncracked section, concerns have been voiced about the residual gravity load capacity of units with cracked webs (Elwood & Hogan, 2021). The cracking of hollow-core webs at moderate drift demands as demonstrated in this paper indicates that some hollow-core floors in existing buildings which have previously experienced moderate to strong ground shaking (e.g. Wellington and Christchurch) are likely to already have some degree of web cracking. There is, however, no information available to reliably quantify the residual gravity load-carrying capacity of a hollow-core unit with damaged webs. Experimental testing is in preparation to investigate the residual capacity of a hollow-core unit with cracked webs.

5 CONCLUSION

This paper summarised observations related to the seismic performance of hollow-core floor units seated within the plastic hinge region of intermediate columns (beta units) from a case study building and two full-scale tests. Observations from both the case study building and the tests highlighted the susceptibility of hollow-core floor units to sustain a higher degree of damage when seated within the plastic hinge regions of the supporting beam, where the precast floor units are subjected to localised deformation to accommodate the deformation of the supporting seismic and gravity systems. Beta units were observed to sustain damage at low drift levels, approximately 0.6% and 1% longitudinal and transverse to the unit direction, respectively, and generally incurred more damage than units seated outside the plastic hinge zone. Furthermore, the observations from both the case study building and the tests suggest that beta unit damage is sensitive to the boundary conditions of the unit, bending demands in the transverse and longitudinal direction of the unit, as well as inertial diaphragm forces.

The fragility of beta units is not recognised in the current concrete design standard, NZS3101:2006-A3. While collapse of units were not observed in the case study building, damage observed to beta units suggests that the deemed to comply seating detail in the Commentary of NZS3101:2006-A3 does not reliably satisfy the life safety performance objective of the New Zealand Building Code (MBIE, 2021). Furthermore, SESOC et al. (2021) has advised that “due to the fragility of hollow-core units, the use of hollow-core floors in new buildings is not considered to represent good structural engineering practice and therefore we do not recommend its use”. The beta unit fragility is also not acknowledged in the most up-to-date assessment procedures, which may lead to a retrofit design that does not fully address the higher risks posed by such units.

Further work is currently taking place to investigate how much residual gravity load-carrying capacity a hollow-core unit with damaged webs can sustain. This work will provide information to allow better quantification of the risk these floors pose.

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