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Seismic Performance of Precast Prestressed Hollow-core Floors and Residual Capacity of Web-cracked Floor Units

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ABSTRACT

Precast prestressed hollow-core floor units are a common precast floor system. Hollow-core floor units were observed to sustain critical damage during earthquakes, where deformation compatibility within the system was shown to significantly impair the performance of these floors.

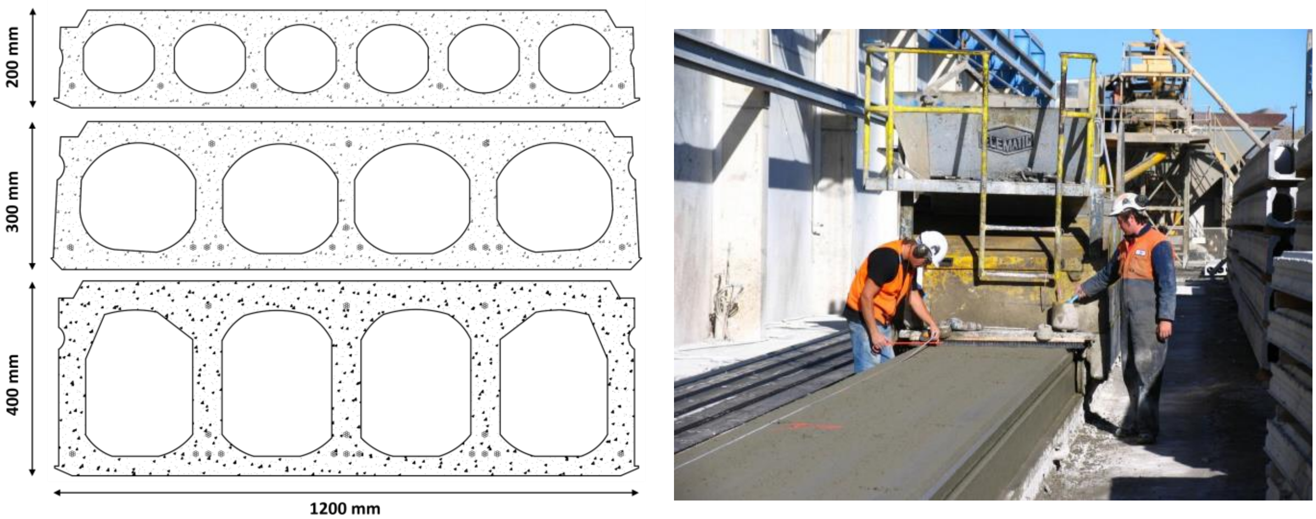
This paper presents recent seismic damage observations to hollow-core floor units incorporating current design and detailing requirements from a case study building and proposes links between the observed response and specific design concerns. Analyzing the observed damage to hollow-core floor units from the case-study building, the susceptibility of hollow-core floor units to sustain a higher degree of damage when seated at or adjacent to an intermediate column (within the plastic hinge regions of the supporting beams), even when incorporating current seismic detailing requirements, was highlighted. The observed damage suggests that hollow-core flooring systems incorporating current support design and detailing requirements may not satisfy the targeted performance of the New Zealand concrete design provisions to consider deformation compatibility between precast flooring systems and the supporting structural system if the units were seated within the plastic hinge region.

Furthermore, this paper discusses preliminary results from twelve full-scale tests investigating the post-cracking residual load-carrying capacity of hollow-core units. The results indicate that the support seating length significantly affects the post-cracking residual shear capacity of hollow-core units. The findings from the experimental campaign suggest that hollow-core floor units that sustained damage in their unreinforced webs during an earthquake may not have sufficient residual gravity load capacity to ensure life safety during or after an earthquake.

Keywords: Prestressed concrete, Precast members, Hollow-core floor units, Seismic performance, Residual shear strength

INTRODUCTION

Precast Prestressed Hollow-core floor (HC) units are concrete slabs with longitudinal voids, or cores, running along the length of the floor unit, as shown in Figure 1. These cores reduce raw material consumption and floor units' weight, making these floor units structurally efficient. HC flooring system is commonly used in precast floor construction due to their structurally efficient cross-section, high strength-to-weight ratio, reduction in site labor and formwork, speed of installation, and cost-effectiveness [1-2]. The production processes used to manufacture HC units, namely extrusion and slip-forming, contribute to the economic competence of these floor units, where material waste and manufacturing labor time are reduced. However, these production methods do not allow installing shear reinforcement into the HC units. This inability to install shear reinforcement makes HC floor units inherently vulnerable to brittle failure modes when subjected to seismic actions, as described in [3-4].



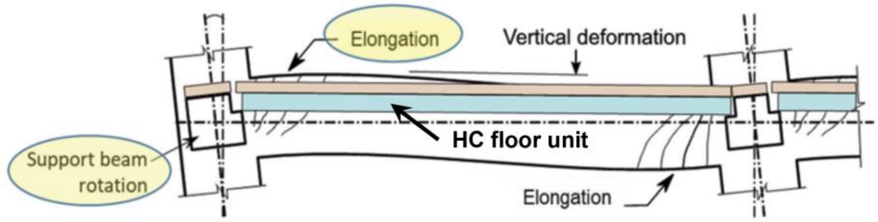
(a) (b)

Figure 1. a) Schematic of different Hollow-core floor units cross-sections. b) Extrusion machine extruding zero slump concrete forming the hollow-core floor unit cross-section [5]

The susceptibility of HC floor units to sustain critical damage due to seismic actions has been realized and extensively investigated over the past two and half decades in New Zealand [4], [6–15]. The previous research conducted on the seismic performance of HC floor units led to three key outcomes: (1) Identification of the main failure mechanisms that can occur in HC floor units under seismic actions [3] (Figure 2 shows some of the failure modes that can occur at the supports of HC floor units). (2) Quantifying the inter-story drift that can cause each of the failure mechanisms identified (i.e. assess the HC floor units' seismic capacity) as described in [3-4], [16]. (3) Development of improved floor-to-support connection detailing for new construction achieving enhanced seismic performance and provisions to avoid placing HC floor units directly beside an adjacent beam, wall, or other structural elements where deflections under seismic actions may result in different vertical displacements between the HC floor unit and the adjacent structural element [17].

Although previous research has substantially contributed to understanding the seismic performance of HC floor units, damage observations of these floors in the wake of the 2016 Kaikoura earthquake in New Zealand revealed unexpectedly poor seismic performance of floors incorporating more recent design and detailing requirements. Damage to the unreinforced webs of these floor units was frequently observed in units seated at or adjacent to an intermediate column (within the plastic hinge regions of the supporting beams). Such damage is expected to have significantly impaired the gravity load-carrying capacity of these units. Concerns regarding the residual gravity load capacity of these floor units upon cracking of their unreinforced webs were raised [18]. Particularly as the design of HC floor units to resist gravity loads in shear assumes an uncracked section. However, limited information is available to quantify the residual gravity load-carrying capacity of HC floor units with damaged webs.

This paper presents observations from a detailed damage investigation of a case study building that included current design and detailing requirements and relates these observations to a potential gap in current international concrete design standards. Furthermore, to assess the residual gravity load-carrying capacity of HC units with cracked webs, a series of full-scale tests were conducted, and preliminary results were presented.



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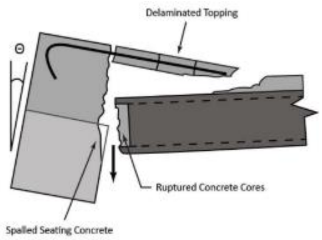
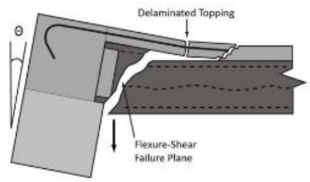
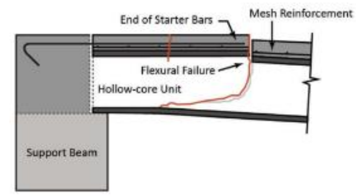






(b) (c) (d)

Figure 2. a) Schematic of deformation demands induced into the precast floors due to seismic actions [4] and Sketch of potential seismic failure modes of HC floor units. b) loss of support c) positive moment failure [12] d) negative moment failure [13]

SEISMIC PERFORMACE OF PRECAST HOLLOW-CORE FLOORS

Background

The collapse of HC floor units during the 1994 Northridge earthquake, as shown in Figure 3a, raised serious concerns in New Zealand about the expected seismic performance of these floors in future events where HC floors had been widely used in New Zealand since the late 1970s [19]. Subsequently, significant research investigating the seismic performance of HC floors has been undertaken over the past 25 years in New Zealand. A series of component tests were conducted to better understand the behavior of specific HC floor connections under seismic actions [4], [6–8], [20]. However, it was not until the early 2000s that critical failure mechanisms of these floors were exposed in a large-scale super-assembly test (Figure 3b) [10].

(a) (b)

Figure 3. a) Hollow-core floor collapse during 1994 Northridge Earthquake [21] b) Hollow-core floor collapse in large-scale test [10]

The vulnerability of HC floor units when subjected to seismic actions was highlighted during this past research, and damaging mechanisms associated with HC units seated immediately adjacent to a moment frame were identified. Through these previous investigations, improvements to the floor unit support connection details have been developed and proof tested to address the potential failure mechanisms identified in previous research [11-12], which was subsequently introduced into the New Zealand Concrete Structures Standard in 2006 [17]. Moreover, provisions to avoid placing HC units directly beside an adjacent beam, wall, or other structural elements where deflections under seismic actions may result in different vertical displacements between the HC floor unit and the adjacent structural element were included in the New Zealand Concrete Structures Standard in 2006.

Recent Seismic Performance Observations and Design Concerns

A detailed damage investigation was conducted on a case study building with HC floors following the 2016 Mw-7.8 Kaikoura earthquake in New Zealand. The building investigated was a commercial office building with ductile reinforced concrete moment-resisting frames and HC flooring system constructed in 2009. The layout of the building consisted of three seismically linked buildings, referred to as 'piers', that were connected via composite steel-concrete pedestrian 'link bridges' and separated by two atrium spaces, as shown in Figure 4. Pier 1 and Pier 3 were five stories tall, while Pier 2 had an additional sixth story. The link bridges were designed with sufficient strength to tie the piers together in the longitudinal direction.

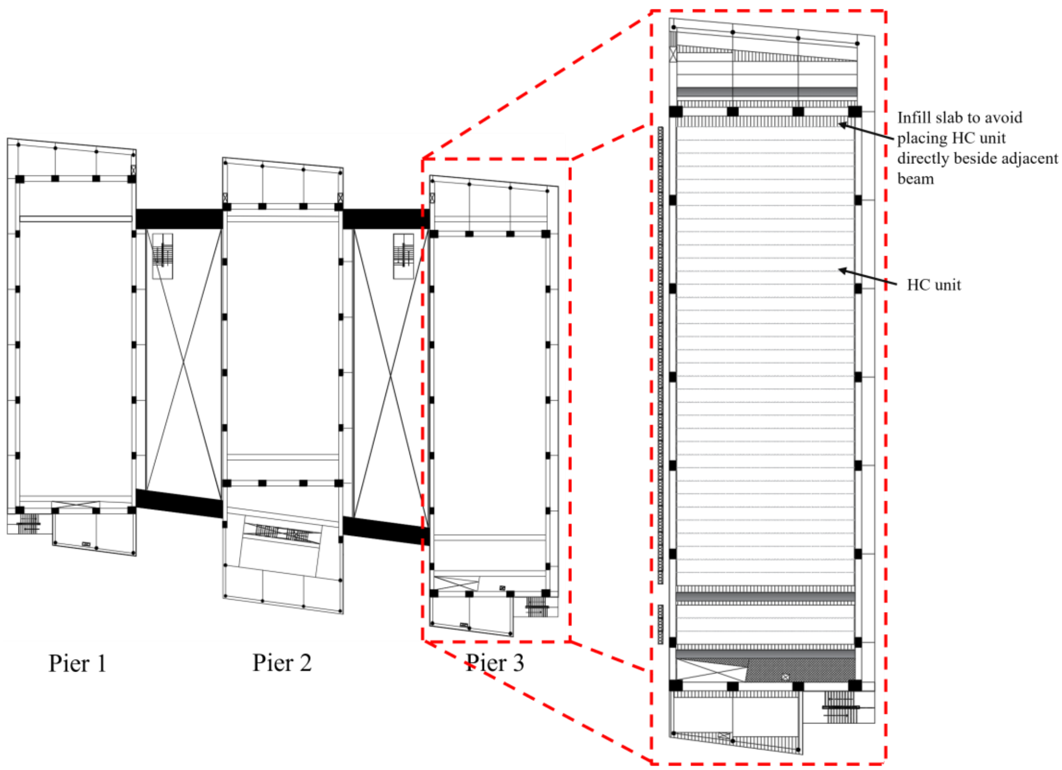
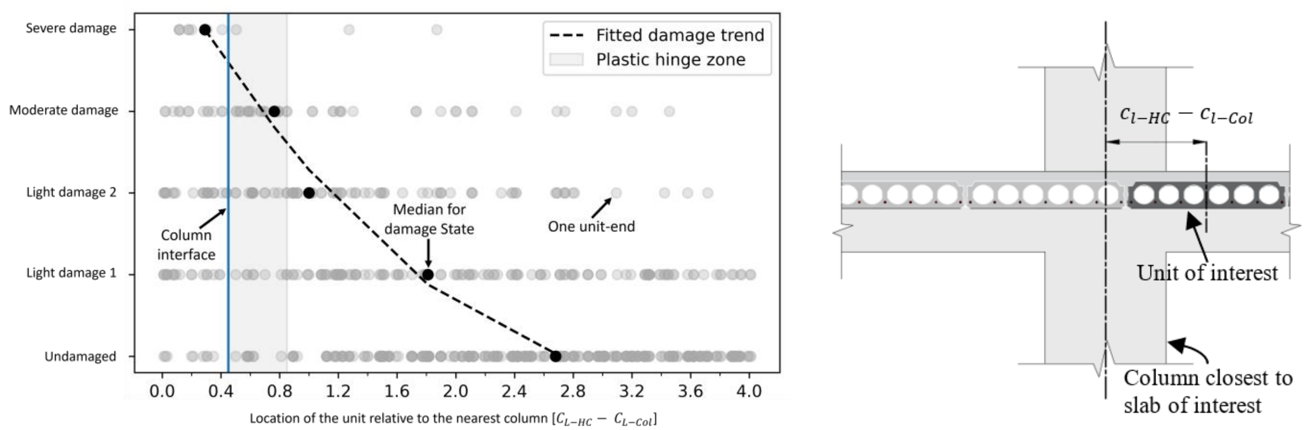


Figure 4. Schematic showing building layout

Damage observations from the building showed unexpectedly poor performance of HC floors that incorporated current seismic detailing requirements according to the New Zealand concrete structures design standard, NZS3101:2006 (*Figure 5*).

To quantify the extent of damage sustained in the floors, a qualitative damage assessment criterion was developed to classify different observed damage states in the case study building. Each HC unit-end was assigned a damage state from light-severe based on how likely the gravity load path was compromised. A light damage state represented negligible or cosmetic damage, and severe damage indicated that the unit gravity load-carrying capacity had been significantly compromised. The damage severity for each HC unit-end was plotted against each unit location relative to the nearest column for 684 unit-ends (i.e. 342 HC units), as shown in *Figure 6*. It was noted that there was a trend for the damage severity, where the closer the unit support was to a column (i.e. supported in beam plastic hinge region), the higher the degree of damage. [22]

Figure 5. Examples of damage observed in HC floor units with current detailing seated within the plastic hinge region showing cracking of the unreinforced webs of the floor units



(a) (b)

Figure 6. a) Damage trend of HC units relative to the floor unit location (centerline of HC unit relative to centerline of nearest column). The plastic hinge length was taken as half of the supporting beam depth (effective plastic hinge length ~0.5 beam depth) b) illustrative schematic of the HC unit location used

HC floor units seated within the plastic hinge region can be subjected to significant bending and twisting demands due to the deformations of the supporting structure. Moreover, HC floor units seated within the plastic hinge region were found to receive critical damage, where cracking of the unreinforced webs of these floor units was observed. Cracking the unreinforced webs impairs the gravity load-carrying capacity during and after an earthquake (*Figure 5*).

The susceptibility of HC floor units to sustain a higher degree of damage when seated at or adjacent to an intermediate column (within the plastic hinge regions of the supporting beams), even when incorporating current seismic detailing requirements, was highlighted. The observed damage suggests that although the current New Zealand concrete design standards may include provisions that require consideration for deformation compatibility between precast flooring systems and the supporting structural system, HC flooring systems incorporating current seismic design and detailing requirements may not satisfy the targeted performance of international concrete design provisions requirements to consider deformation compatibility if the units were seated within a plastic hinge region.

POST-CRACKING RESIDUAL SHEAR CAPACITY OF PRECAST HOLLOW-CORE FLOOR UNITS

The design of HC floor units to resist gravity loads in shear assumes an uncracked section. However, HC floor units were observed to sustain web cracking and other critical damage when subjected to earthquake-induced deformations in laboratory experiments (Figure 7) and post-earthquake field observations (*Figure 5*).

(a) (b)

Figure 7. Propagation of cracking into the unreinforced webs of the HC floor unit under simulated earthquake demands. a) negative moment failure [23] b) Positive moment failure [24]

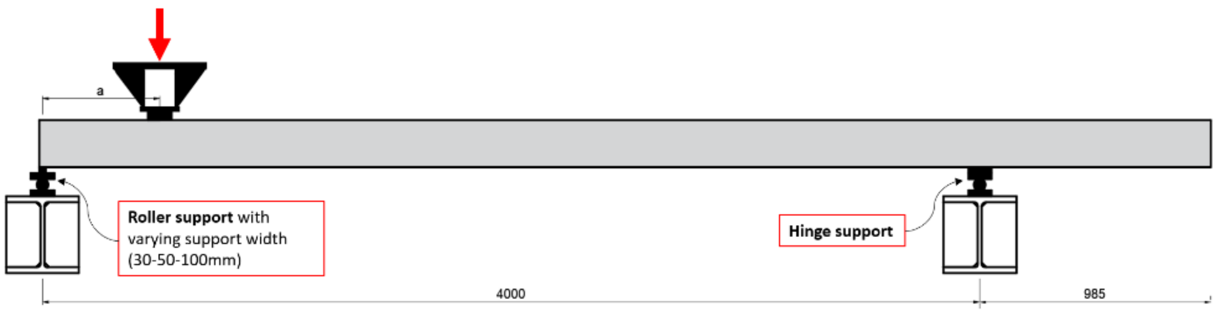
There is little information available to reliably quantify the residual gravity load-carrying capacity of HC floor units with cracked webs following an earthquake highlighting the need to understand the post-cracking behavior of HC floor units to better quantify the risk of damaged floor units.

The experimental campaign was conducted to investigate the post-cracking behavior of HC floor units. Twelve full-scale HC floor units were tested to assess the influence of different support seating lengths and shear span-to-depth ratios on the post-cracking residual shear capacity of HC floor units. All floor units were 200 mm deep, manufactured using the extrusion method, and designed according to the New Zealand Concrete Structures Standard, NZS 3101:2006. The testing program is summarized in Table 1.

The general configuration for the test setup is illustrated in Figure 8. The support, which is the nearest to the load application point, was a roller bearing to avoid generating any unintended axial forces by a rotation of the HC unit at the support. Between the HC unit and the support plate, a load-distributing material (gypsum) was used to compensate for the unevenness of the HC unit surface and any possible curvature of the HC unit in the transverse direction. The load was applied at a distance 'a' from the roller support, as recommended by the European Standard EN-1168. The load was applied using a closed-loop MTS actuator with a capacity of 500 kN (112.4 kips). A rigid beam was attached to the actuator to apply the line load to the test specimen. The length of the tested units was kept at 4000 mm (157.48 in.), as recommended by the European Standard EN-1168:2005. Two tests per HC unit were conducted by rotating the unit 180 degrees, as damage to the HC unit would occur only along the shear span, allowing for enough length to perform a second test on each unit.

Table 1. Summary of the HC Testing Program

Test Set One – Effect of support seating length on post-cracking residual shear capacity			
Test Case	**Shear Span**	**# of tests**	**Loading**
HC200 with 30mm seating	2.5d	2 tests	Monotonic push
HC200 with 50mm seating	2.5d	2 tests	
HC200 with 100mm seating	2.5d	2 tests	
Test Set Two – Effect of shear span on post-cracking residual shear capacity			
Test Case	**Shear Span**	**# of tests**	**Loading**
HC200 with 50mm seating	1.5d	2 tests	Monotonic push
HC200 with 50mm seating	3.5d	2 tests	
HC200 with 50mm seating	2.5d	2 tests	cycle loading upon cracking



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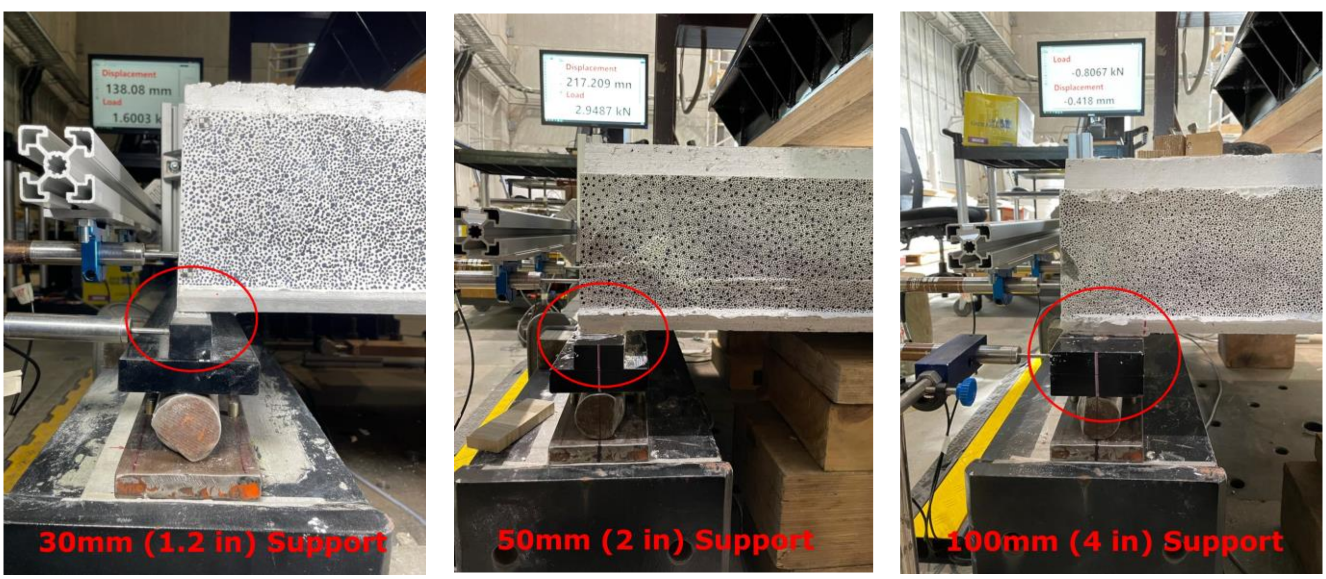


(b) (c) (d)

Figure 8.a) Schematic for Test set-up b) 30mm roller support c) 50mm roller support d) 100mm roller support

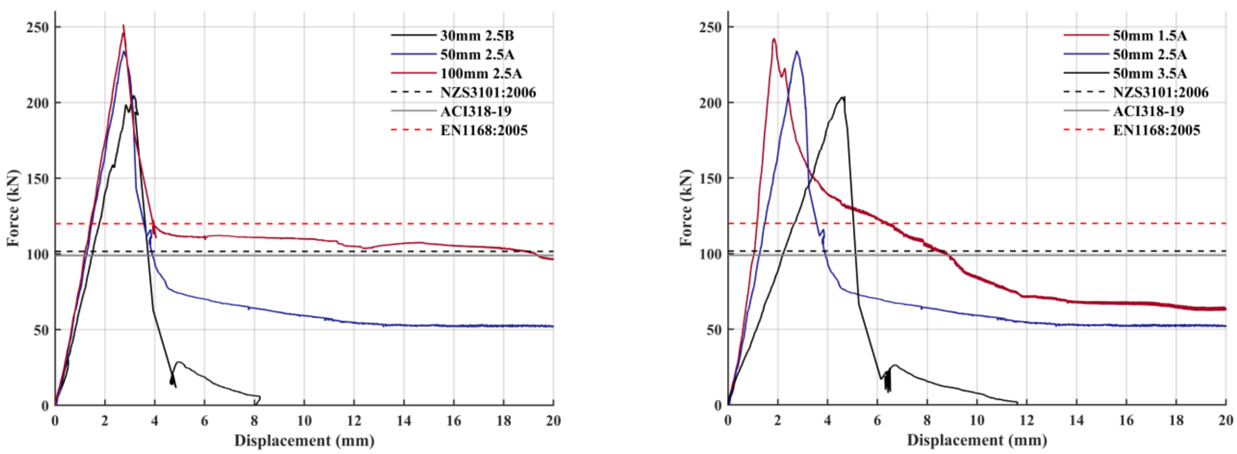
The tested units were loaded monotonically well beyond the peak shear force (cracking) to study the post-cracking behavior of the HC units. All tested units were loaded in a displacement control manner with a loading rate of 0.2 mm/s.

Across the tests, a relatively similar post-peak behavior was observed in the shear-displacement response, where a significant drop in load-carrying capacity upon diagonal cracking of the unreinforced webs of the HC units, as presented in Figure 9. Generally, after the drop applied force, due to the cracking of the unreinforced webs, the applied shear force remained at an almost constant residual value with increasing applied displacement.

The shear span was fixed for the first test set, and the support seating length was varied between 30, 50, and 100 mm. Tests with a 100 mm (~4in) support seating length could maintain almost the full estimated section shear capacity of the HC unit according to design standards (NZS3101:2006, ACI318-19, EN1168:2005). Whereas tests that had 50 mm (~2in) support seating length maintained about 50% of the estimated capacity of these floor units. Finally, tests that used a 30 mm (~1.2in) support seating length could not maintain the applied force with increasing displacement upon cracking. Figure 9a shows the shear strength versus deflection curve for some of the tested units with different support seating lengths.

For the second test set, as 50 mm is a commonly specified seating length for existing HC flooring systems in New Zealand [25], the support seating length was fixed to 50 mm (~2in), and the shear span was varied between 1.5d, 2.5d, and 3.5d. Tests with 1.5d and 2.5d generally maintained a residual load of around 50% of the estimated section capacity. However, tests with 3.5d did not maintain any significant residual capacity. Figure 9b shows the shear strength versus deflection curve for some tested units with different shear spans.

It is worth noting that it was found that in existing buildings, the seating is typically less than 50 mm [25]. Hence the results from the tests that used 30 mm support seating lengths are critical, particularly for a region of high seismicity such as New Zealand.



(a) (b)

Figure 9. Some of the recorded responses from the testing campaign showing a) effect of support seating length on post-peak response b) effect of shear span on post-peak response

The observed residual load was compared to the estimated section capacity according to the New Zealand concrete design standards (NZS3101:2006), American concrete design standards (ACI318-19), and European design standards (EN1168:2005), and a relationship between the support seating length and the expected residual shear strength as a ratio from the estimated section shear capacity of the HC floor units was plotted as shown in Figure 10.

From Figure 10, a significant loss in residual gravity load-carrying capacity is expected for HC floor units upon cracking of their unreinforced webs if the support seating length is less than 50 mm. This finding can be critical for post-earthquake structural assessment. It should be noted that although HC units with 100 mm support could maintain a residual load almost equivalent to the calculated section capacity, there are very few buildings (in New Zealand) incorporating HC flooring systems with 100 mm support seating length.

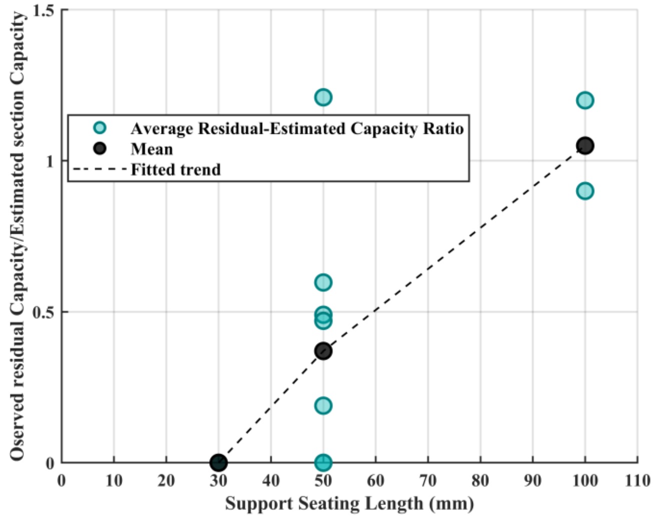


Figure 10. Observed residual-estimated capacity ratio according to concrete design standards relative to tested support seating lengths

ONGOING RESEARCH TO ENHANCE THE SEISMIC PERFORMANCE OF EXISTING PRECAST HOLLOW-CORE FLOOR UNITS

Further research is underway investigating the use of supplemental transverse shear reinforcement as a retrofit solution for HC floor units. An experimental campaign is underway investigating the ability of different variations of post-installed supplemental shear reinforcement to provide a reliable load path after the formation of web cracks in HC units. Variations considered in testing included different shear reinforcement spacing, transverse spacing of reinforcement legs, and level of pretension, providing insights into different factors considered in the design of this potential retrofit technique.

CONCLUSIONS

Some seismic damage observations of precast prestressed hollow-core floor units incorporating current seismic design and detailing requirements from a case study building was presented. Furthermore, twelve 200 mm deep hollow-core floor units were experimentally tested to investigate their residual gravity load-carrying capacity after web cracking. The effect of different support seating lengths and different shear spans, from 300 to 700 mm (1.5 to 3.5 aspect ratio), was studied. Preliminary results were presented and compared with analytical formulations according to modern building codes.

The main findings of this study can be summarized as follows:

- The susceptibility of hollow-core floor units to sustain a higher degree of damage when seated at or adjacent to an intermediate column (within the plastic hinge regions of the supporting beams), even when incorporating current seismic detailing requirements, was highlighted.
- The observed damage suggests that hollow-core flooring systems incorporating current seismic design and detailing requirements may not satisfy the targeted performance of the New Zealand concrete design provisions requirements to consider deformation compatibility if the units were seated within a plastic hinge region.
- All tested floor units experienced a significant reduction in gravity load-carrying capacity upon cracking the unreinforced webs.
- The support seating length significantly affected the post-cracking residual shear strength.
- The residual shear strength of units with different support seating lengths was compared to equations used in international design standards (NZS3101:2006, ACI318-19, EN1168:2005) to predict the shear capacity of hollow-core floor units. It was found that if the available seating is greater than 100 mm, the floor unit can maintain almost the full design shear capacity of the floor unit.
- Units with a support seating length of 50 mm had a significant reduction in load-carrying capacity, with an average residual capacity of less than 50% of the design shear capacity of the unit.
- Units with support seating length of 30 mm completely lost their shear capacity upon cracking the unreinforced webs.

- When subjected to seismic demands, many existing hollow-core floor units are expected to be left with less than 30 mm seating. Hence, it is expected that hollow-core units with damaged webs will not have significant residual gravity load capacity to ensure life safety.

ACKNOWLEDGMENTS

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