Title of Research (EQC grant reference number)

Retrofit Testing of Hollowcore Floors # 18/U769

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Summary

The collapse of precast concrete flooring components in Statistics House and varying levels of damage to precast floor units in many other buildings during the Kaikoura earthquake has increased concerns about the performance of these elements in earthquakes. While the details for these floor systems have been improved in new buildings, support conditions for units in existing buildings designed before 2006 are likely to lead to significant damage and potentially collapse in design level ground motions.

Buildings with precast floors comprise a large percentage of the commercial building stock in all New Zealand cities, with likely over 60% of commercial buildings in Wellington falling in this category. There are increasingly more residential buildings with older precast floor details as more buildings are being converted from commercial to residential in Wellington CBD. A Wellington Fault event will undoubtedly lead to multiple floor collapses in numerous buildings throughout Wellington.

Assessing the likely performance of these floors in an earthquake is a challenge for engineers. While guidance has recently been developed for the seismic assessment of buildings with precast floors

(so-called Yellow Chapter), engineers will urgently need direction on retrofit approaches to address vulnerable buildings. In particular, concern has been raised that seat angles, already provided as a retrofit for several buildings, could potentially lead to unintended negative moment failures and collapse of hollowcore floors. This research identifies under what conditions such unintended failure modes may be triggered and provides a retrofit solution where vulnerability to negative moment failure is identified.

An experimental investigation was directed at issues related to 200 mm deep hollowcore units (known as loss of seating (LOS) and Negative Moment Failure (NMF)) that could lead to casualties in earthquakes. A focus was on identifying seating connection details that would lead to the unfavourable failure mechanisms and validating retrofit options to remediate existing floors at risk. A previously used retrofit known as the "seating angle retrofit" to avoid LOS was also examined to determine if it would promote NMF in cases where it was installed "hard up" against the bottom of the hollowcore unit. It was found that the relative flexibility of the most commonly used seating angles reduced the severity of NMF promotion. This was a good outcome as it meant that many existing cases of the retrofit in New Zealand buildings will not require further remediation. However, it was found that seating connection details with stiffer seating angle retrofits or strong or short starter bar configurations are prone to NMF. These cases represent a smaller subset of floors in New Zealand but will require additional retrofit. Three retrofit strategies were tested to fix NMF prone cases. These were:

- Cutting starter bars at the interface between the hollowcore unit and support beam to release restraint and demand on the unit at the end of the starter bars – where negative moment cracking initiates.
- Post-installing bars into the unit topping to increase the strength of the unit at the critical section for crack initiation for NMF.
- Lowering the seating angle retrofit by 10 mm to remove the additional restraint it imposed on the unit.

All of these retrofits proved successful for preventing NMF. The diaphragm weakening side effects of cutting starter bars means that this retrofit is only appropriate for some areas of a floor though.

Introduction

Two types of precast flooring unit have been widely used in New Zealand construction of multi-storey buildings since the early 1980's. These precast units are called hollowcore and double-tee units and they are seated on beam ledges with an in-situ concrete topping cast on top. Precast floor units are connected to the beams of the structure using continuity reinforcement or "starter bars", which are cast into the beams and floor topping. Typical cross-sections for these precast units and a typical schematic of a ledge support connection are displayed in Appendix A. The poor performance of some precast flooring units in Wellington multi-storey buildings during the 2016 Kaikoura Earthquake has confirmed the concerns throughout the engineering industry about the safety of these flooring systems for building occupants.

An experimental investigation was directed at issues related to hollowcore units, as they were identified as the precast flooring system with the most pressing concerns. 200 mm deep hollowcore (200HC) units were selected for testing because they are the most commonly used size in New

Zealand multi-storey buildings. Also, previous investigations have mainly focussed on 300 mm deep hollowcore units – leaving a gap in the body of knowledge and lack of data regarding 200HC.

Two of the critical failure mechanisms that engineering practitioners aim to avoid with hollowcore units under earthquake loading are known as "loss of seating" (LOS) and "negative moment failure" (NMF). LOS is undesirable because it describes a unit falling off insufficient ledge seating during an earthquake, which compromises the life safety of building occupants on and below the affected floor. NMF is undesirable because it describes cracking and eventual collapse of the unit away from the ledge support – meaning it will also drop onto the floor below, compromising the life safety of building occupants. Hollowcore is known to perform poorly when subjected to negative moment demands (which imposes tension on the top of the unit), because it only has reinforcing steel near the bottom in the form of pre-tensioned strands, as shown in Appendix A. This means the unit itself must withstand tension demand at the top of the unit by the tensile capacity of concrete alone - which is relatively small and unreliable. The only steel reinforcing at the top of a hollowcore floor system (beyond the end of the starter bars) is mesh in the topping, which is insufficient for large earthquake demands. Depictions of LOS and NMF are displayed in Figure 1.

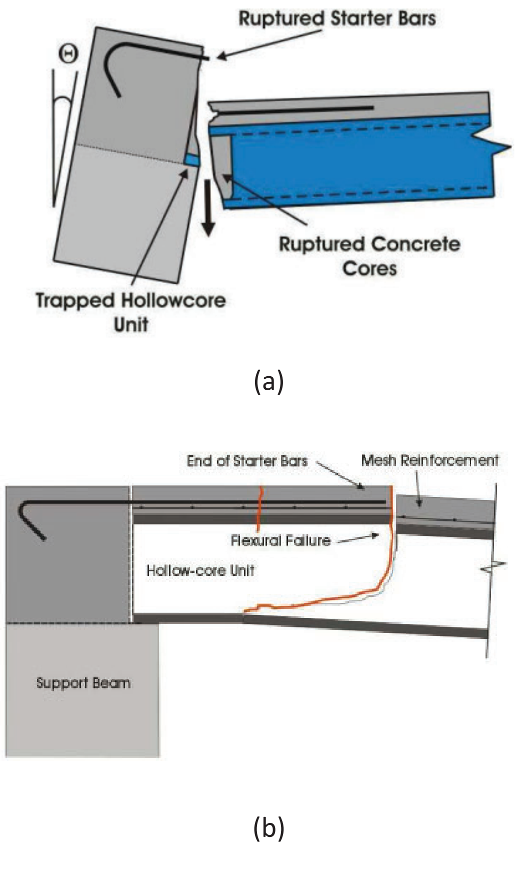


Figure 1: LOS (a) and NMF (b) Mechanisms (Sourced from Woods, 2008)

The critical parameter determining if LOS will occur is the available seating length. The critical parameters determining if NMF will occur are the seating length, the length of the starter bars and the strength of the starter bars across back face of the hollowcore unit (where the unit ends against the support beam). A longer seating length is beneficial to prevent LOS but provides a more critical case for NMF. The interaction of the strength vs length of the starter bars is particularly important for NMF, because it is a scenario where the strength of one member in the structure needs to be weaker than the rest, thereby acting as a “fuse”; allowing the structure to deform safely in an earthquake. In this case, it is favourable for the “fuse” and damage concentration to occur at the back face of the unit (a crack forming at the interface of the back of the unit and face of the supporting beam; stretching (plastically deforming) the continuity bars). With the crack forming at this interface, the unit remains supported by the seating ledge. However, if the starter bars are too strong across the back face of the unit or too short, the damage will instead be pushed out to the section at the end of the starter bars where there is a sudden drop in floor strength. Capacity-demand curves depicting the strength drop-off at the end of the starter bars are displayed in Appendix B. Unfortunately, a retrofit detail commonly used in the early 2000’s to address LOS has also had the unintended consequence of promoting NMF. This retrofit called the “seating angle retrofit” is a steel angle bolted to the support beam underneath the unit, providing additional seating for the hollowcore unit. This retrofit is shown in Figure 2.

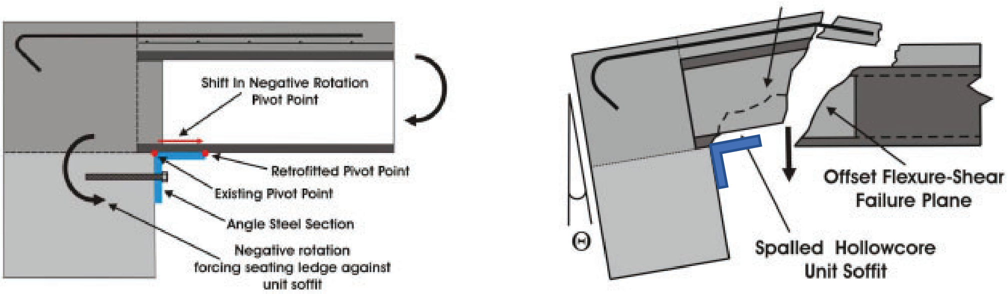


Figure 2: Promotion of NMF by the Seating Angle Retrofit (Sourced from Jensen, 2006)

The issue with the seating angle retrofit is that it can hasten the onset of NMF when the angle is installed in direct contact or “hard up” against the hollowcore unit soffit (bottom of the unit). In this case, the unit becomes restrained by the angle when it is rotated (as it would be in an earthquake), changing the support reaction (or pivot point) under negative rotation from the end of the ledge further out towards the end of the angle, as shown in Figure 2. This has two undesirable consequences:

- It is effectively a shortening of the starter bars – which as previously mentioned, results in the Negative Moment Failure (NMF).
- It creates a negative moment peak demand over the end of the angle which is essentially to say the angle works to “break the back” of the unit. This extends the length over which the unit is subjected to negative moment demand (meaning tension at the top of the floor over a longer length away from the support). This is critical, because if the unit is still being subjected to a large negative moment demand at the end of the starter bars, the tension capacity of the topping mesh may be insufficient to prevent crack initiation and propagation through most of the depth of the unit. A comparison of the negative moment demands with and without an angle are displayed in Appendix B.

Once negative moment cracking occurs and the mesh is snapped, the effective section available to carry load becomes very small and the stiffness of the hollowcore unit decreases greatly. The negative moment crack propagates from the top of the floor at the end of the starter bars down to the depth of the prestressed strands as shown in Figure 1 (b). From there, the crack continues horizontally along the web, at the height of the prestressed strands, until it reaches near the edge of the ledge or angle support. Under repeated cyclic earthquake loading or even gravity loading, sudden collapse of the unit is a high likelihood at this stage, because the entire floor is primarily being held up only by dowel action of the prestressing strands that cross the main crack in the bottom of the unit, at the support.

Multiple tests were required to determine how each mechanism forms: the NMF and the more favourable mechanism of cracking at the back face of the unit over the support ledge. As part of this testing programme, the testing of retrofits to remedy the NMF cases was done. To accomplish this, the single unit testing method used previously by University of Canterbury and University of Auckland researchers was employed. This method used a hollowcore unit supported on one end by a beam segment with the desired ledge seating connection for testing and supported on the other end by a vertically oriented actuator. An additional horizontal actuator attached to the end of the hollowcore unit was also used to impose axial tension on the unit for one test case. This applied axial/longitudinal tension was used where it was appropriate to account for beam elongation (a process through which concrete beams stretch during earthquakes, pushing the hollowcore ledge supports apart). This setup is displayed in Figure 3.

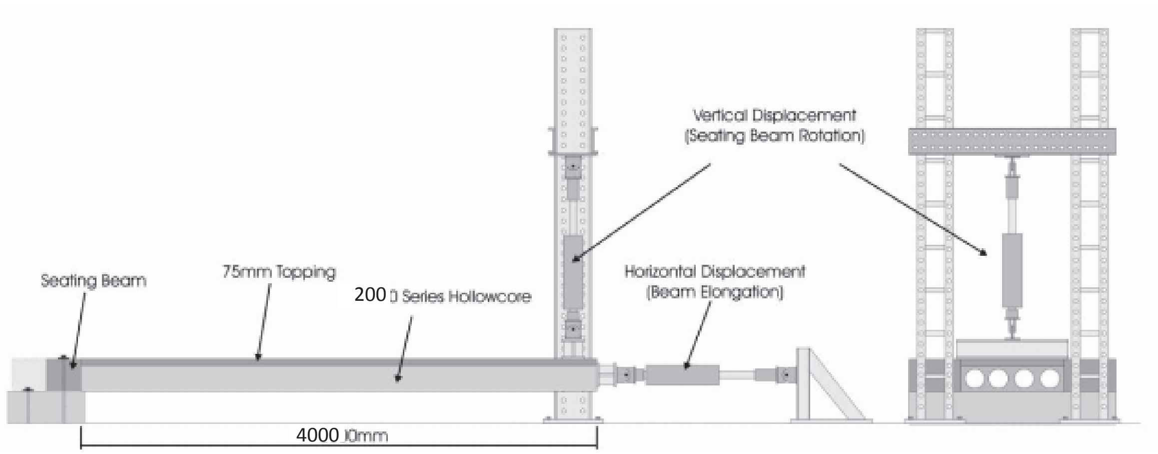


Figure 3: Single Unit Test Layout

The vertical actuator was used to impose rotational demands on the beam-hollowcore seating connection by rotating the hollowcore unit. In a real earthquake, the support beam would be the component rotating (by moving with the columns as the building deforms laterally). As the demands in the seating connection are only caused by the differential movement between the support beam and hollowcore unit though, it is inconsequential which component is rotated. A comparison of a building rotating in an earthquake to the test method of applying rotation is shown in Figure 4.

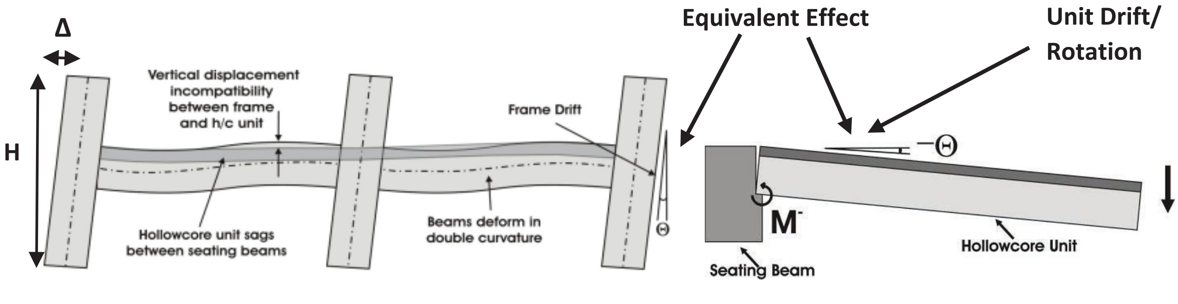


Figure 4: Comparison of Rotation/Drift in a Building and Single Unit Test

A common engineering method of reporting the amount of building rotation during an earthquake is to provide a percentage ratio of how far the building has deformed laterally compared to the storey height. This is called "drift". For example, for a storey height (H) of 4 m, a 1% drift would correspond to the building deforming sideways (Δ) by 40 mm over that height. This is the format the results from the single unit tests will be reported in. Downward rotation of the unit (causing negative moment in the unit) as shown in Figure 4 is recorded as negative drift and upward rotation is recorded as positive drift.

Objectives

There are two key objectives to this research. These are:

- Identify the seating connection details which lead to Negative Moment Failure (NMF) under earthquake loading. Ideally, determine the conditions that cause the preferred cracking at the interface between the back face of the unit and front face of the supporting beam, over that of NMF.
- Provide initial verification for retrofit strategies to fix seating details identified as being prone to NMF.

Specimen Layouts and Results

Six specimens were tested. Four specimens were used to model existing cases in buildings, to find the conditions that promoted an acceptable seating connection detail that concentrates damage at the back face of the unit, over that of an unacceptable detail that causes NMF. The remaining two specimens used the same layout as the critical NMF case (or used a worse case for triggering NMF) but with the addition of retrofits designed to prevent NMF.

Unless otherwise stated, the specimens had the following layout:

- 200HC unit supported on a 50 mm ledge
- 75 mm topping concrete
- 665L ductile mesh in the topping (8 longitudinal 5.6 mm wires running down the unit length)
- 600 mm long (from the unit back face) Grade 500 HD12 starter bars at 400 mm centre-to-centre spacing (3 starter bars per unit). This bar strength and layout was chosen because 600 mm long bars were commonly used in real buildings and Grade 300 bars had been found through previous research to have insufficient strength to trigger NMF. Any greater reinforcement ratio (by having closer spaced bars) was expected from analysis to trigger NMF even without an angle retrofit. The aim was to show a continuity reinforcement detail that would only have cracking at the back face without a seating angle retrofit but display NMF once an angle was added under the unit soffit. This was because one of the objectives was determining what the issues may be with the seating angle retrofit.
- Where an angle was used, it was a Grade 300 steel 150x150x12 mm equal angle attached hard up to the soffit under the full width of the unit. Stiffened angles had five regularly spaced triangular 16 mm thick stiffener plates welded on the inside of the angle.
- Where a cracked section was required, a 30 mm deep saw cut was made along the full width of the topping 50 mm beyond the end of the starter bars (no topping mesh was cut).

- A 5 kN (500 kg) billet frame was strapped to the top of the unit, centred at 1.45 m away from the back face of the hollowcore unit. This load was used to model the gravity load demands for a typical office floor using the New Zealand Standard probabilistic load combination for earthquake loading of G + 0.3Q (where G is self-weight of the floor and Q is a standard live load of 3 kPa imposed by occupants and furniture). This relatively low imposed load was appropriate while testing for NMF because a low gravity load is the critical case for this failure mechanism.

Apart from the final test, all specimens were loaded only with the vertical actuator in the setup displayed in Figure 3. This was because for NMF, only having rotational load applied is the critical case. The typical loading protocol for the tests was as follows:

- A large initial monotonic push in negative drift to determine if negative moment failure was going to initiate (this provided a critical loading case for NMF similar to a large singular earthquake pulse).
- If it would provide useful results (judged based on the condition of the unit after the monotonic push), a cyclic protocol of two cycles at ±1% drift, two cycles at ±2% drift, two cycles at ±3% drift and one cycle at ±4.5% drift (note that as the length between the back face of the hollowcore unit and the vertical actuator connection was 3.6 m, a drift of 1% corresponded to a vertical actuator displacement of 36 mm).

The general layout of the seating connection details is displayed in Figure 5 and Figure 6 and the specific details for each specimen are shown in Table 1. The layout of the post-installed bar retrofit is shown in Figure 5 including a depiction of the designed strut-and-tie solution. The stiffened angle stiffener layout is shown in Figure 7. An overview of the individual test layouts, objectives and results is displayed in Table 2.

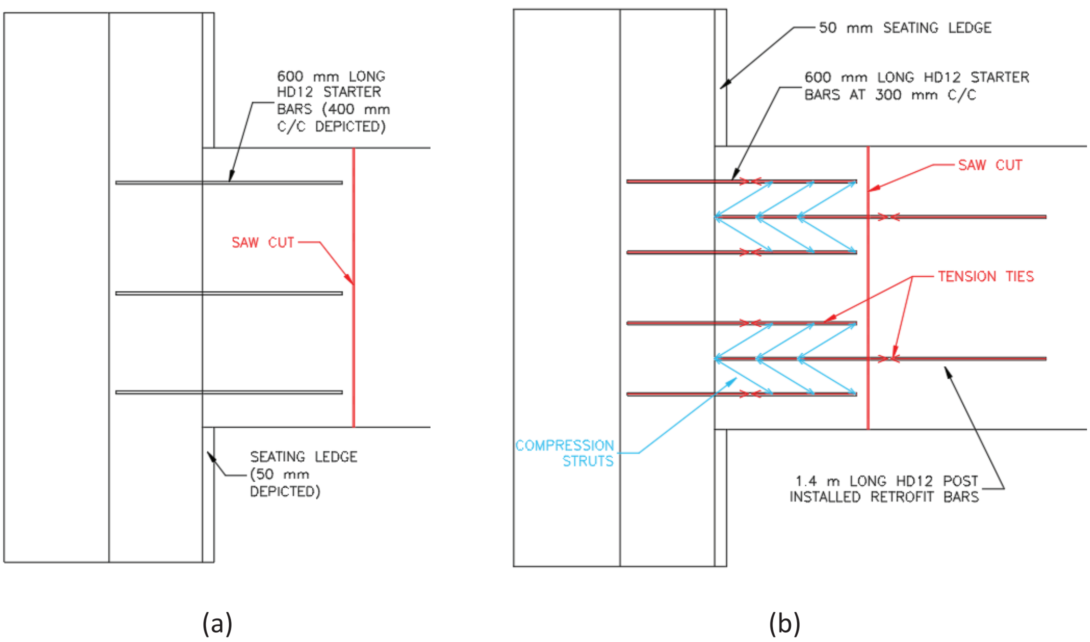


Figure 5: Plan View of General Specimen Seating Connection Layout (a) and Post-Installed Bar Retrofit Layout with Strut-and-Tie Solution (b)

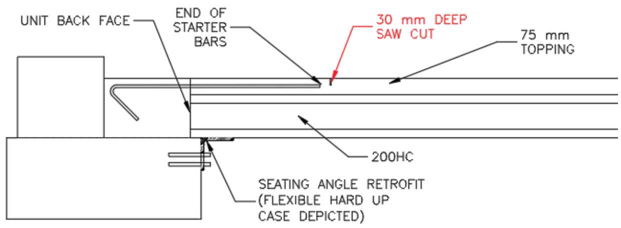


Figure 6: Elevation of General Specimen Seating Connection Layout

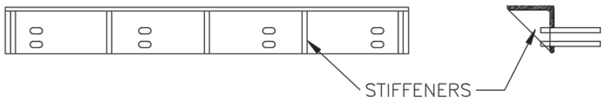


Figure 7: Elevations of the Stiffener Layout for Stiffened Angles

Table 1: Specimen Seating Connection Configurations

All Specimens – 600 mm long HD12 starter bars				
Test Set One – Existing Cases				
Test Case	**Starter Bar Configuration**	**Angle**	**Ledge Seating**	**30 mm Deep Saw Cut at End of Starter Bars (Crack Initiator)?**
1 - Unretrofitted, uncracked section	400 mm c/c spacing (3 bars)	None	50 mm	No
2 - 150 mm angle (flexible), uncracked section	400 mm c/c spacing (3 bars)	Flexible – hard up	50 mm	No
3 - 150 mm angle (flexible), cracked section at the end of the starter bars	300 mm c/c spacing (4 bars) – one bar cut at unit back face (3 bars effectively)	Flexible – hard up	50 mm	Yes
4 - 150 mm angle (stiffened), cracked section at the end of the starter bars	400 mm c/c spacing (3 bars)	Stiff – hard up	50 mm	Yes
Test Set Two – Retrofit Cases				
Test Case	**Starter Bar Configuration**	**Angle**	**Ledge Seating**	**30 mm Deep Saw Cut at End of Starter Bars (Crack Initiator)?**
5 - 150 mm angle (stiffened), 2 x 1.4 m long post-installed bar retrofit, 4 starter bars, cracked section at the end of the starter bars	300 mm c/c spacing (4 bars)	Stiff – hard up	50 mm	Yes
6 - 150 mm angle (stiffened) placed with a 10 mm gap below the unit soffit, cracked section at the end of the starter bars, elongation tension applied, 30 mm ledge seating	300 mm c/c spacing (4 bars) – one bar cut at unit back face (3 bars effectively)	Stiff – lowered by 10 mm from the unit soffit	30 mm	Yes

Table 2: Testing Matrix for Auckland Single Unit Hollowcore Experiments

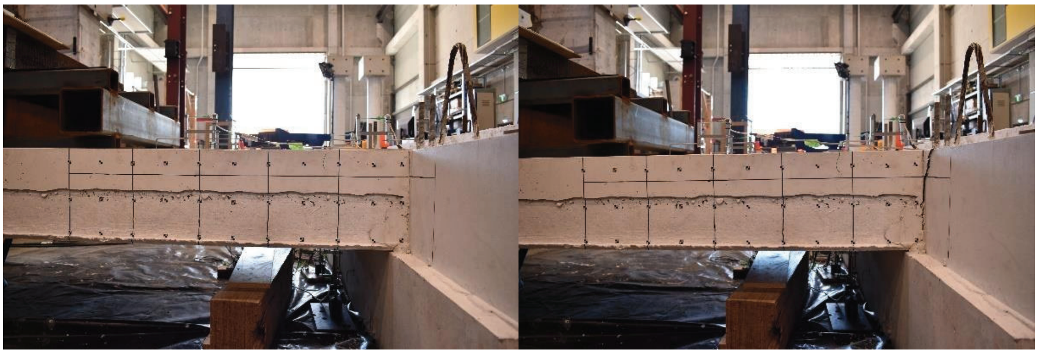
Test Set One – Existing Cases			
Test Case	**Expected Failure**	**Objectives**	**Results**
1 - Unretrofitted, uncracked section	LOS or cracking at the unit back face	Control case to display either no critical failure or LOS issue.	No Critical Failure – Crack opened at the back face of the unit. Large amount of remaining seating after cycling.
2 - 150 mm angle (flexible), uncracked section	NMF	Display NMF caused by an angle.	No Critical Failure - Crack opened at the back face of the unit. No negative moment cracks progressed into the unit.
3 - 150 mm angle (flexible), cracked section at the end of the starter bars	NMF	Display NMF caused by an angle for a cracked section.	No Critical Failure – Crack opened at back face of the unit. Negative moment cracking progressed a short way into the unit.
4 - 150 mm angle (stiffened), cracked section at the end of the starter bars	NMF	Display NMF caused by a stiff angle for a cracked section.	Critical NMF – negative moment cracking appeared at -1.0% drift, large loss of stiffness and 3 mm vertical crack offset at -1.8% drift and complete loss of stiffness at -2.25% drift.
Test Set Two – Retrofit Cases			
Test Case	**Desired Mechanism**	**Objectives**	**Results**
5 - 150 mm angle (stiffened), 2 x 1.4 m long post-installed bar retrofit, 4 starter bars, cracked section at the end of the starter bars	Cracking at the unit back face	Display how reducing the strength drop-off at the end of starters prevents NM failure.	Cracking at the unit back face, no critical failure – negative moment cracking was held closed by the retrofit bars. Secondary cracking developed in the top of the unit similar to a beam plastic hinge. Success.
6 - 150 mm angle (stiffened) placed with a 10 mm gap below the unit soffit, cracked section at the end of the starter bars, elongation tension applied, 30 mm ledge seating	LOS and unit caught by the angle	Display how removing angle restraint avoids NM failure and tests if there are issues with the unit landing on the angle.	LOS and unit caught by the angle, no critical failure – no issues with the unit landing on the angle or any damage causing the unit to crack and drop beyond the end of the angle. Success.

Test Case 1 – Unretrofitted, Uncracked Section

The first test was set-up as a control case to display the performance of the hollowcore seating connection layout without the addition of any angle or other alterations. The seating connection configuration for this test is outlined in Table 1. The expected failure mechanism was cracking at the back face of the unit with some spalling of the ledge and back face of the hollowcore unit. Due to shrinkage and some small load applied during transportation of the unit, there was a hairline crack at the back face of the unit before testing began. This did not have any effect on the observed failure mechanism, as explained in the Test 4 section.

Monotonic Loading

For the first component of the test, the unit was displaced with negative rotation until it reached a drift of -2.75%. The seating connection displayed the expected mechanism of a crack opening at the back face of the unit throughout the rotation. This crack started as an existing hairline crack and widened as the drift increased. The top of the crack reached a width of 6 mm at -2.75% drift and the bottom of the crack remained hairline in width, because the unit was pushed against the beam front face at the bottom during the rotation. An approximately 45-degree triangular wedge of spalling occurred at the back face of the unit over the full width of the ledge (50 mm). The starter bars had clearly yielded at this displacement demand. A comparison of the seating connection before testing and at -2.75% drift is displayed in Figure 8.



(a) (b)

Figure 8: Specimen 1 Before Test (Left) and at -2.75% Drift (Right)

Cyclic Loading

The cyclic displacement portion of the test followed the standard protocol previously described. No additional cracks were observed through this portion of the test. The only notable development was the widening of the residual crack as the level of applied displacement was increased through the drift cycles. At the end of the cyclic protocol, the crack at the back face of the unit had a residual width of 6.5 mm for the full depth. The unit was still well seated and displayed no indication of an unfavourable mechanism such as NMF, as shown in Figure 9.

Figure 9: Specimen 1 Residual Crack after Full Cyclic Protocol Up to ±4.5% Drift

Test Case 2 – 150 mm Flexible Angle, Uncracked Section

The second test was the first attempt at identifying a lower-bound seating connection detail which would trigger NMF due to the undesirable side-effects of using a seating angle retrofit. The seating connection was identical to Test 1 except for the addition of a Grade 300 150x150x12 mm steel angle bolted hard against the soffit of the unit. The connection configuration for this test is outline in Table 1. The topping of the unit had some minor distributed shrinkage cracking prior to the start of the test.

Monotonic Loading

The unit was displaced to -2.75% drift for the monotonic push down component of this test. Like Test 1, a crack formed at the back face of the hollowcore unit and progressively widened at the top as the displacement demand was increased. None of the distributed shrinkage cracks propagated out of the topping concrete and in to the unit due to the imposed loads. An unexpected result from this test was that the angle displayed more flexibility than accounted for. This meant that instead of the assumed rigid connection providing full restraint to the hollowcore unit, the angle only provided partial restraint - and a lower than expected reaction at the end of the angle. This reduced reaction proved insufficient to trigger NMF. The bending of the angle under load imposed by negative rotation of the hollowcore unit can be seen in Figure 10.

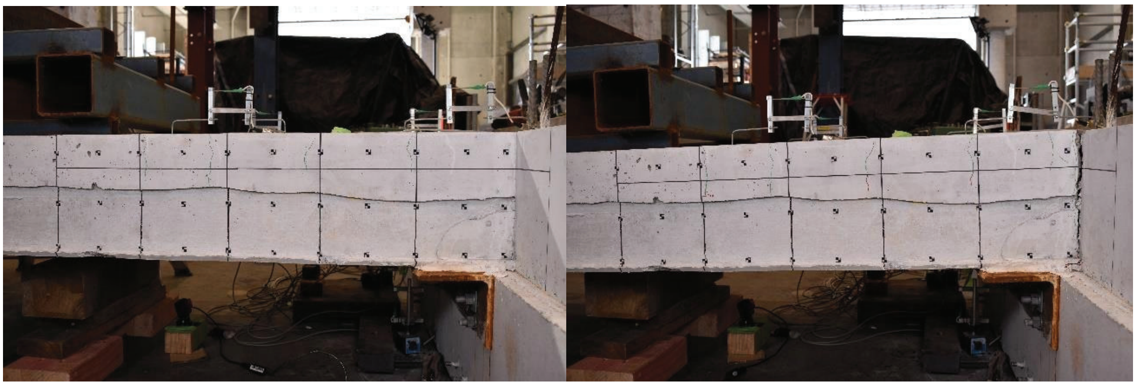


Figure 10: Specimen 2 Before Testing (Left) and at -2.75% Drift (Right)

The test was concluded without the addition of a cyclic loading protocol once the unit was returned to 0% drift. This was because it was judged that NMF would not occur for this seating connection detail, so no new information on NMF would be provided from a cyclic protocol.

Test Case 3 – 150 mm Flexible Angle, Cracked Section

The same connection detail was used as Test 2, except for the addition of a 30 mm deep saw cut located at 50 mm beyond the end of the starter bars used to model a cracked section. This cut was added because it was decided that relying on the floor topping to be uncracked was unreliable due to the possibility of shrinkage cracking or existing cracks from previous earthquakes in the topping. The specimen was also cast with four starter bars, so one bar was cut at the back face of the unit before testing to reduce the number to three like the previous tests. The cuts in the top of the specimen are displayed in Figure 11 and the connection configuration for this test is outline in Table 1.

Figure 11: Specimen 3 - Saw Cut at the End of the Starter Bars

Monotonic Loading

The unit was displaced to -3.5% drift for the monotonic push down component of this test.

Until -0.5% drift, cracking was only observed at the back face of the unit, similar to the previous tests. Directly beyond -0.5% drift, the initiated crack at the end of the starter bars propagated down to the interface between the topping and unit on the west side. On the east side, the initiated crack propagated only part way into the topping. A second crack also appeared on the east side at 140 mm from the back face that extended almost half-way into the unit as shown in Figure 112.

Figure 112: Specimen 3 at -0.53% Drift – Initial Crack Propagation (West – Left, East – Right)

At -0.75% drift, a crack at 230 mm from the back face of the unit propagated into the unit approximately 25 mm on the west side. The low stiffness of the connection because of the angle flexibility appeared to cause more concentration of damage closer to the back face of the unit. The crack at the saw cut section split into two cracks on the west side but neither continued into the unit. On the east side, the crack at the saw cut section propagated down 5-10 mm into the unit. The progression of cracking at -0.75% drift is displayed in Figure 13.

Figure 13: Specimen 3 at -0.75% Drift (West – Left, East – Right)

At -1.25% drift, the crack at the saw cut section on the east side propagated further to approximately 30 mm into the unit as shown in Figure 14.

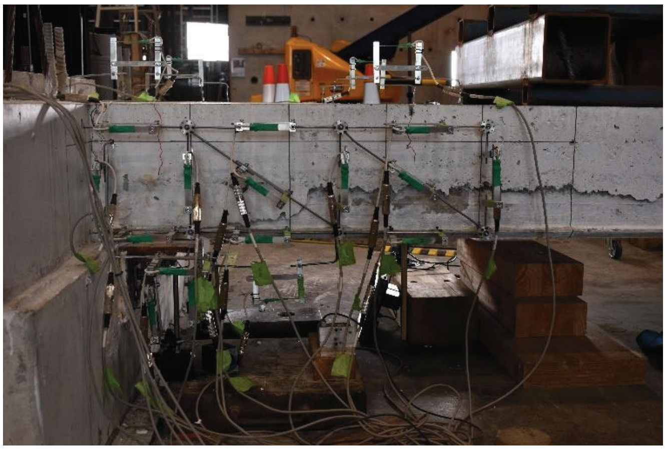


Figure 14: Specimen 3 at -1.25% Drift – Critical Crack Propagation (East Side)

No additional unit cracking was observed until at -1.75% drift, when another negative moment crack began developing between the previous two cracks on the west side. It stopped developing beyond -2.0% drift and did not leave the topping. This crack can be seen in Figure 15.

Figure 15: Specimen 3 at -1.75% Drift (Left) and -2.0% Drift (Right) (West Side)

Beyond -2.0% drift, no additional damage was observed in the unit. All damage had concentrated at the back face of the unit. The test was therefore concluded after reaching -3.5% drift and then returning to 0% drift, as negative moment failure had been avoided with this connection detail. The specimen at -3.5% drift is displayed in Figure 16.

Figure 16: Specimen 3 at -3.5% Drift – All Damage Concentrated at Back Face (West – Left, East – Right)

None of the cracking observed away from the back face of the unit developed across the full width of the topping as can be seen in Figure 17.

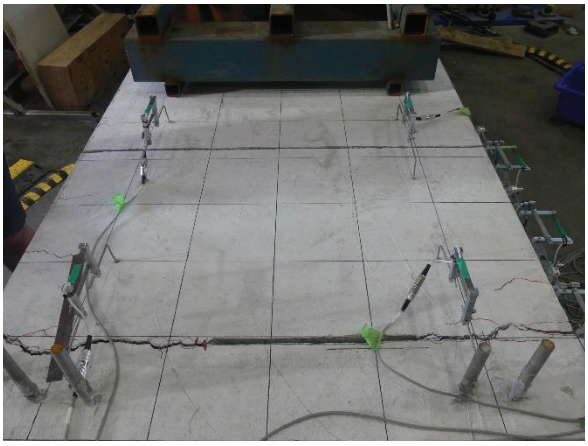


Figure 17: Top of the Specimen 3 at -3.5% Drift

Test Case 4 – 150 mm Stiffened Angle, Cracked Section

Test 4 was used to determine if a stiffer connection would trigger NMF. The same seating connection configuration as Test 3 was used except the angle was stiffened by welding five stiffener plates to the inside to increase restraint on the unit. This configuration is outlined in Table 1.

Monotonic Loading

Initial cracking occurred at the back-face of the unit occurred at approximately -0.45% drift displacement. This caused an instant loss of stiffness and the unit dropped to -0.6% drift before picking up load again. Negative moment cracking occurred at -1.0% drift displacement. At this stage, the crack at the back face of the unit had opened to approximately 2 mm wide. The negative moment crack did not appear during loading, instead forming approximately 30 seconds after loading stopped. A loud cracking was heard and the unit lost stiffness, increasing the drift to -1.6%

instantaneously. The unit directly before and after the negative moment crack propagated is displayed in Figure 18 and Figure 19. This result was useful, because it showed that for negative moment cracking to occur, the crack at the back face of the unit needed to open first. The starter bars needed to be stressed and stretched across the back face of the unit to activate most of their strength. This created enough negative moment demand (tension at the top of the unit) at the end of the starter bars to crack the unit there. This hierarchy of failure mechanisms displayed that retrofit strategies aimed at pre-cracking the back face of the hollowcore unit would not sufficiently change the structural system to prevent NMF. After this point, loading was continued up to -1.75% drift where it was confirmed that all additional deformation was now occurring at the negative moment crack instead of the unit back-face crack.

Figure 18: West Side of Specimen 4 Directly Prior (Left, -1.0% Drift) and After (Right, -1.6% Drift) NM Crack Initiation

Figure 19: East Side of Specimen 4 Directly Prior (Left, -1.0% Drift) and After (Right, -1.6% Drift) NM Crack Initiation

Cyclic Loading

The specimen was returned to 0% displacement and a cyclic load protocol of was started. This consisted of 2 cycles at 1.0%, 2 cycles at 2.0% and a cycle up to 3.0% which the specimen failed at before reaching. An additional cycle of 5.0% was added at the end to display how the hollowcore unit was effectively a pin-roller connection depending only on the strength of the 7 prestress strands to keep it from falling. No significant additional damage was observed in the two 1.0% drift cycles. In the first 2.0% drift cycle, the crack had a sudden extension at -1.8% drift causing the unit to drop instantly to -2.15% drift which is displayed in Figure 20. At this stage the crack reached the depth of the prestress strands and propagated along them half way to the angle support. A vertical offset of

3 mm was observed at the top of the unit across the NMF crack (initiated by the saw cut). This vertical offset can be considered failure of the unit.

Figure 20: East Side (Left) and West Side of Specimen 4 (Right) at Second -2.0% Drift Peak Displacement Cycle

In the second 2.0% drift cycle, the unit had reduced stiffness in the negative portion of the displacement from the first cycle. The stiffness further decreased after a minor additional crack propagation occurred at approximately 1.15%. In the 3.0% drift cycle, the unit reached -2.25% drift before complete loss of stiffness occurred and the actuator supported end dropped. The wires of the mesh were heard snapping one after another as this occurred. The unit would have landed on the floor at the actuator end but was caught by dunnage placed under the unit near the actuator to avoid this. It was caught at -4.25% drift which is shown in Figure 21. The residual negative moment crack after returning to 0% drift is displayed in Figure 22.

Figure 21: East (Left) and West Side of Specimen 4 (Right) at -4.25% Drift

Figure 22: East Side of Specimen (Left) and West Side of Specimen (Right), the Residual Crack at 0% Drift

The negative moment crack was observed to have propagated down to the bottom of the unit near the end of the angle as shown in Figure 23. This meant the unit was mainly being held up by the pre-stress strands acting in dowel action.

Figure 23: Full Depth Crack Propagation at Collapse

The unit was taken to positive 4.0% drift. Note in Figure 24 how the bottom section which contains the prestress strands pried up the top section which contains the starter bars. After the complete loss of stiffness in the negative portion of the 3.0% drift cycle, these had become two separate sections.

Figure 24: Positive 4.0% drift (Left) and Residual (Right) Showing Prying Effect of Separated Sections

During the positive 4.0% drift cycle it was found that the crack at the soffit widened and new full depth cracks developed in the region of the thin section containing the prestressing strands just beyond the ledge as shown in Figure 25. The prestress strands also became fully visible at the top of the reduced support section. Note that from previous drift cycles, it was found that no new damage occurred in the positive drift cycles. It is expected that other than the new soffit cracks in the reduced support section, no significant new damage occurred in this cycle. The prying of the top starter bar section simply made the damage from the negative portion of the cycle more visible.

Figure 25: Extensive Soffit Cracking at +4.0% drift

The unit was then taken to -6.0% drift where the test was finished. The unit provided no stiffness throughout the displacement, instead acting like a pin around the ledge support as shown in Figure 26. The snapped mesh from the complete loss of stiffness at -2.25% drift was clearly visible as displayed in Figure 27.

Figure 26: Unit Connection at -6.0% drift – End of Test

Figure 27: Snapped Mesh visible at Test End

Test Case 5 – 150 mm Angle (Stiffened), Post-Installed Bar Retrofit, Cracked Section

Specimen 5 was used to test a potential retrofit strategy to prevent the NMF triggered in Test 4. This retrofit was the post-installation of two 1.4 m long HD12 bars into the topping, starting from the back face of the unit. Two 30 mm deep and wide channels were cut into the unit topping. The retrofit bars were then placed within the channels and cast in using epoxy. Note, it is important for this retrofit that the post-installed bars do not cross the interface between the unit back face and the support beam front face. This is because this would increase the demand that the starter bars at the unit back face could impose at the end of the starter bars – negating the positive effects of the retrofit. This configuration is outlined in Table 1 and the retrofit strut-tie solution is shown in Figure 5. The retrofit at different stages of installation is displayed in Figure 28.

Figure 28: Post-Installed Bar Retrofit Before (Left) and After (Right) Filling Channels with Epoxy

Monotonic Loading Overview

The retrofit performed well and prevented negative moment failure up to the monotonic limit of -3.5% drift. Many cracks formed in the topping and progressed into the unit, but none went beyond half the depth of the unit. Instead, they propagated a short way for 0.25-0.75% drift then stopped after another section cracked. This repeated as the retrofit bars became engaged over more of their length until there were crack lines across the full width of the unit at regular intervals of approximately 200-250 mm as shown in Figure 29 and Figure 30. On reaching approximately -2.25% drift, most of the damage stopped in the unit and concentrated at the back face instead (noting that this was the same drift that the un-retrofitted case had complete loss of stiffness – this may be a coincidence). A difference from previous tests was that whenever loading was stopped, the load reading would relax to the same load every time - approximating to an equivalent 50 kNm at the end of the starter bars. The unit would spring up slightly, no matter how far the starter bars had been pushed past yield and into strain hardening (Test 3 had NMF crack initiation at the end of the starters at around 54 kNm). Near the end of the monotonic displacement of the test, the unit was springing back up by approximately 2.5 mm at the actuator end, within 10 seconds of stopping loading. The retrofit bars appeared to be acting like springs attached to the top of the unit, and at the end of each push the distributed cracks would close as the retrofit "spring" bars recovered some of the tension strain, without increasing tension load being applied. The more cracks that were distributed along the unit, the more spring-back was observed. Overall, the top of the unit in the first 1-1.4 m from the back face behaved much more similarly to a beam in the plastic hinge zone than Specimen 4, which only had mesh reinforcing and had a non-ductile negative moment failure mode. The distributed cracking in the topping can be seen in Figure 31.

Monotonic Loading Progression of Damage

No damage was visible until -0.25% drift. At this stage the back face of the unit cracked, and the sudden loss of stiffness instantly dropped the unit to -0.4% drift. The back-face crack was only hairline at this stage. When load was next applied to move to -0.5% drift, cracking developed in three locations on both the east and west sides as shown in Figure with a fourth developing at -0.75% drift as shown in Figure .

Figure 29: Specimen 5 at -0.5% Drift (West – Left, East – Right)

Figure 30: Specimen 5 at -0.75% Drift (West – Left, East – Right)

The quick progression of the cracks away from the back face of the unit at low drifts displayed the large impact of the stiff angle providing greater restraint. It also showed the engagement of the retrofit bars as they underwent stress and held together the formed cracks by distributing the strain along their length. As the drift increased, more distributed cracks formed, and the existing cracks propagated further into the unit. The cracks did not propagate further than half way through the hollowcore unit depth as shown in Figure 29 and Figure 30.

Figure 29: Specimen 5 at -2.0% Drift (West – Left, East – Right)

Figure 30: Specimen 5 at -3.5% Drift (West – Left, East – Right)

Cyclic Loading

The unit was taken through 2 cycles of 2% drift, 2 at 3% drift, 1 at 4.5% drift and then pushed right down to 6%. No new significant cracking developed in the 2% or 3% drift cycles.

At -4.5% drift, some cracks developed in the epoxy over the NMF sawcut crack initiator. This is shown in Figure 31.

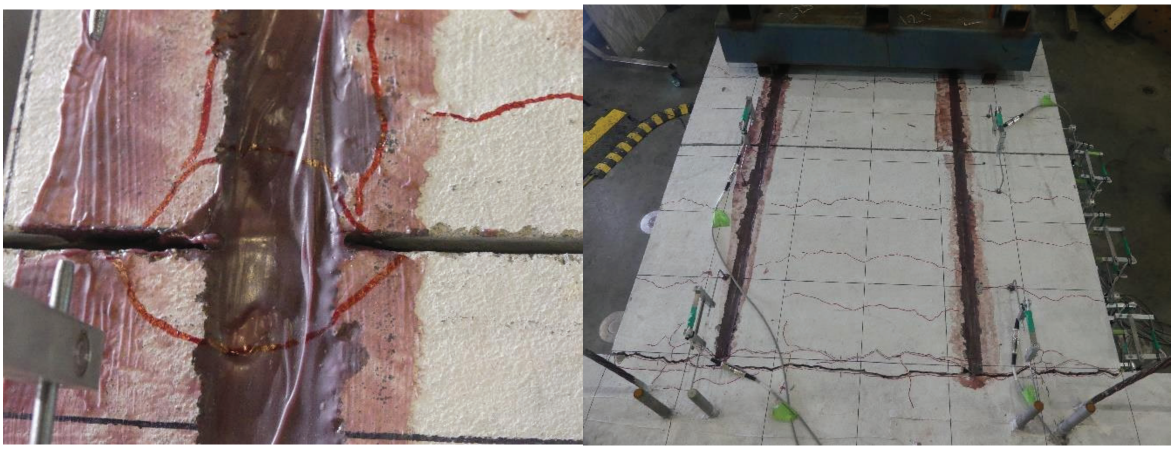


Figure 31: Specimen 5 Cracking in Epoxy (Left) and Distributed Topping Cracking (Right) at -4.5% Drift

The NMF saw cut crack propagated a short way horizontally on both sides, but it was at the mid-height of the unit, in contrast to Test 4 where it propagated right down to the prestressing strands. The critical NMF saw cut crack was 0.1 mm wide at the top at this stage. Other cracks propagated down a short way into the unit as well. Some minute cracks were possibly observed to be running longitudinally along the epoxy but were so faint it was hard to observe or determine if they were cracks. The test ended at -6.0% with no additional NMF saw cut crack propagation. The NMF saw cut crack opened to 0.3 mm at the top at this stage. The specimen at -6.0% drift is displayed in Figure .

Figure 34: Specimen 5 at -6.0% Drift (West – Left, East – Right)

After testing, a crack identifying kit was used on the epoxy surface. Only the easily visible cracks at the critical saw cut section were outlined by this. There was some fine cracking at the interface of the epoxy and concrete, however, the crack identifying kit could not capture these as it was designed to show cracks in smooth materials such as steel rather than more porous materials like concrete. This edge cracking suggests that at drifts beyond -4.5%, the bond between the epoxy and concrete was beginning to deteriorate due to the full strength of the bars being activated. This result shows that use of HD12 G500E bars should likely be considered the maximum strength allowed per channel for the post-installed bar retrofit.

Test Case 6 – 150 mm Angle (Stiffened) Offset by 10 mm from Unit Soffit, Cracked Section

Specimen 6 was used to test a potential retrofit strategy to prevent the NMF triggered in Test 4. This retrofit was the lowered angle configuration of the seating angle retrofit. The aim of this retrofit was to remove the issue of triggering NMF through over-restraint of the unit while still providing additional seating in the form of a catch-frame to avoid LOS. To test the performance of the unit while falling from the ledge onto the seating angle and model the effects of beam elongation in a concrete frame building, tensile load was applied to the end of the unit through a horizontal actuator as shown in Figure 3. A 30 mm ledge was used because a smaller seating width is the critical case for LOS. This configuration is outlined in Table 1.

Cyclic Loading

The critical failure mechanism for this test was LOS. This meant that an initial monotonic push was not appropriate, so only a cyclic rotational loading protocol with elongation effects was used. The rotational cycles used were one cycle at ±0.5% drift, two cycles at ±1.0% drift, two cycles at ±2.0% drift, two cycles at ±3.0% drift and one cycle at ±4.5% drift.

Initial cracking of the unit occurred as a full depth hairline crack at the back face of the unit in the first 0.5% drift cycle. Damage remained concentrated at this crack for the rest of the test. No further interesting damage occurred until the second 2.0% drift cycle. As the unit reached -2.0% drift, the middle starter bar ruptured. This is shown in Figure .

Figure 35: Specimen 6 at -2.0% Drift (Left) and Ruptured Middle Starter Bar (Right)

After the first bar ruptured, restraint of the unit and reaction was greatly reduced. In a real building, this would have the effect of reducing the diaphragm effect provided by the floor. In the first 3.0% drift cycle, the unit began dropping off the ledge support on the eastern side during the first +3.0% cycle as shown in Figure 36. The outer starter bar on the eastern side of the specimen also ruptured as the unit was approaching -3.0% drift.

Figure 36 Specimen 6 at +3.0% Drift (West – Left) and LOS on Eastern Side at +3.0% Drift

The restraint and reaction of the unit was dropping even further after the rupture, suggesting necking and imminent rupture of the final (western) starter bar. However, only having one remaining point of connection between the hollowcore unit and beam section (that was off-centre in plan) changed the structural system of the experiment. As tensile load was applied the unit began to twist in plan around the last remaining starter bar as shown in Figure . This could be considered a limitation of a single unit test. In a real building the unit would have been restrained from twisting in plan by adjacent units or beams. This would have likely caused the final two starter bars to rupture at similar drifts.

Figure 37: Specimen 6 - Out of Plane Twisting of Unit After Rupture of Two Starter Bars (-3.0% Drift)

To allow the completion of the test up to a cycle at 4.5% drift with complete LOS of the unit, the final starter bar was manually cut after both 3.0% drift cycles were complete. The 4.5% drift cycle was completed with the unit completely supported by the angle. There was no indication of restraint against the beam ledge or cracking occurring away from the support as shown in Figure .

Figure 38: Specimen 6 – Full LOS at +4.5% Drift (Left) and Residual Displacement (Right)

Conclusions and Key Findings

- Stiffness of the seating angle retrofit was found to be a major determining factor for whether NMF was triggered or not. The commonly used 150x150x12 steel equal angle was found to be more flexible than expected, causing a lower amount of restraint to be applied to the unit than anticipated.
- Most steel angle seating retrofits currently installed hard up again hollowcore unit soffits in New Zealand buildings would be considered "flexible" by the findings of this investigation. This is a positive outcome, because it means that many existing seating angle retrofit cases should not cause undesirable performance (triggering a NMF) and become a danger to the occupants, and therefore such angles do not require any further remediation. However, for Grade 500 starter bar reinforcing layouts this only applies to when the starters are 600 mm or longer and have a unit back face tensile strength equivalent or lower than that of HD12s spaced at 400 mm c/c. The most common starter bar layout uses a spacing of 300 mm c/c – which would require some form of additional retrofit (against NMF) even for a flexible angle case.
- Drilled holes at the back face of the unit is not a required retrofit strategy for NMF (Jensen 2008) – the natural progression of damage towards an NMF requires a crack to open at the back face of the unit anyway - to engage the starter bar strength. Therefore, this retrofit option makes no valuable changes to the structural system.
- Cutting starter bars across the back face of the hollowcore unit is a valid retrofit strategy for NMF as it reduces restraint and therefore negative moment demand at the end of the unit and end of the starter bars. However, it also has the side effect of reducing the strength of the floor diaphragm. This makes it an appropriate strategy for the corners of a floor plan or in the middle of support beams where the diaphragm strut-and-tie design is unlikely to be relying on the topping reinforcement to act as critical floor ties.
- The post-installed epoxied bar retrofit is a valid retrofit strategy for NMF and has the added benefit of maintaining the designed diaphragm load path. This makes the retrofit appropriate for areas of the floor seating near intermediate columns on the exterior of the building, or the columns within the interior of the floor plan, of which all are likely to be designed as major tie anchor points in the floor diaphragm strut-and-tie design.
- Lowering the seating angle retrofit 10 mm under the unit soffit is a valid retrofit strategy, as it removes the effect of this retrofit detail promoting NMF and instead acts as a catch-frame for the falling floor. Under the test conditions, there was no indication of an issue with the unit landing on the angle once LOS occurred. However, it is recommended for new angle installations that a lowered seating angle with a compressible material infill between the angle and unit soffit is used. This would provide minimal restraint to the unit but also ensure that no impact loading occurs during an earthquake where vertical accelerations could be substantial.
- It is expected that where Grade 500 starter bars have been used for continuity reinforcement; most of these reinforcing bars around the floor perimeters will have ruptured by approximately 2.5-3.0% drift demand because of beam elongation in long duration earthquakes. This drift range is around the ultimate limit state (ULS) design level earthquake displacement demands.
- For long duration ULS design level earthquakes, the strut-and-tie diaphragm design solution will likely be destroyed for much of the later cycles. Future research will investigate how this could impact building performance in earthquakes.

Impact *(i.e., how this research reduces the impact of natural disaster on people and property)*

The ability to identify and retrofit floor units susceptible to negative moment failure greatly reduces the likelihood of "pancaking" failure of affected high rise concrete buildings in design level earthquakes. It is expected that there may be a significant number of Wellington high-rise structures that will require retrofit. Without remediation, affected buildings have high risk of loss of life in design level earthquakes - and by not using the suggested retrofit strategies for affected buildings, considerably more extensive remedies would be required such as replacement of whole floors or the need to demolish the building, at significantly greater cost to building owners, it is anticipated. The impact of this research is to minimize loss of life and cost to building owners by providing relatively cheap retrofit solutions to address the problem of negative moment failure.

Future work

- Additional single unit tests conducted by Frank Bueker, PhD student of the University of Auckland targeting identification and retrofit of positive moment failure and poor bond of hollowcore units.
- The University of Canterbury "big frame" experiments scheduled for August 2019 – August 2020, a joint UoC and UoA experimental project conducted by Mike Parr and Frank Bueker.
- Finite element analysis on the impact of the stiffness of support angle retrofits used for additional seating.

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Jensen, J. (2006). *The Seismic Behaviour of Existing Hollowcore Seating Connections Pre and Post Retrofit.* Christchurch: University of Canterbury.

Woods, L. (2008). *The Significance of Negative Bending Moments in the Seismic Performance of Hollow-Core Flooring.* Christchurch: University of Canterbury.

APPENDIX A – Hollowcore and Double-Tee Unit Profiles

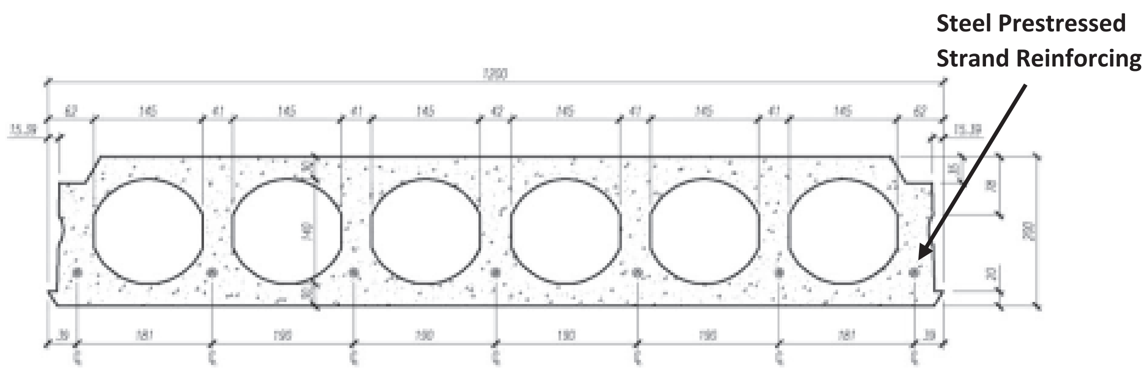


Figure A-1: Typical Hollowcore Cross-Section (Sourced from Stahlton website)

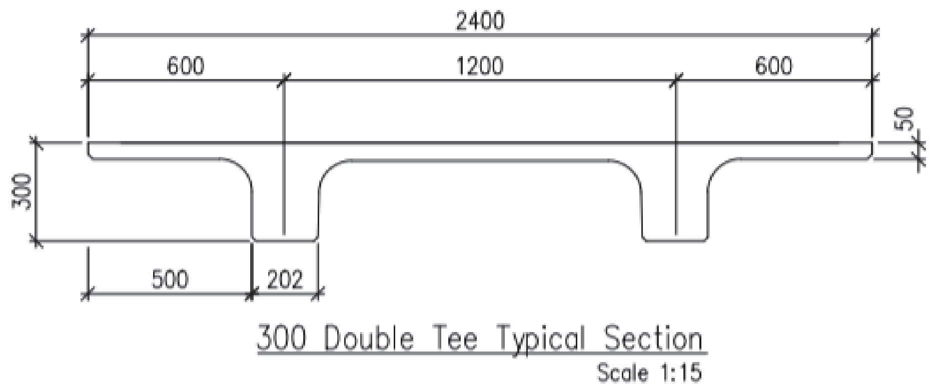


Figure A-2: Typical Double-Tee Cross-Section (Sourced from Stahlton website)

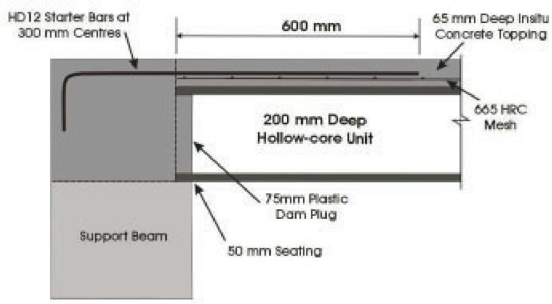
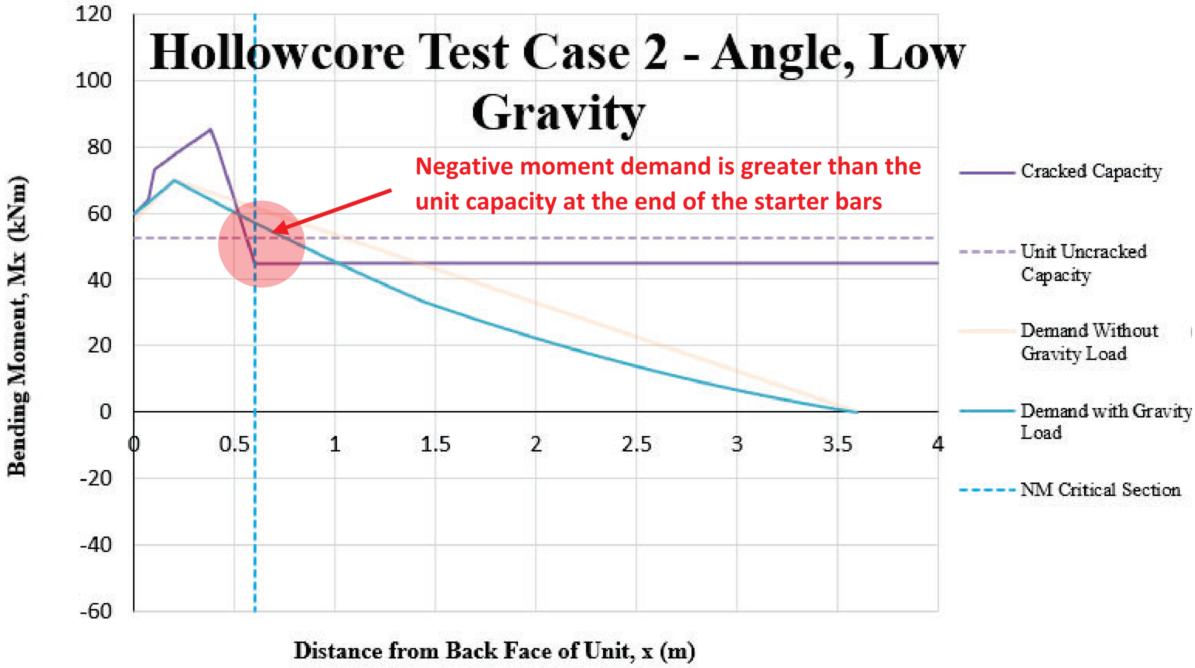


Figure A-3: Typical Hollowcore Seating Connection Detail (Sourced from Woods, 2008)

APPENDIX B – Hollowcore Capacity-Demand Curve for an NMF Prone Case



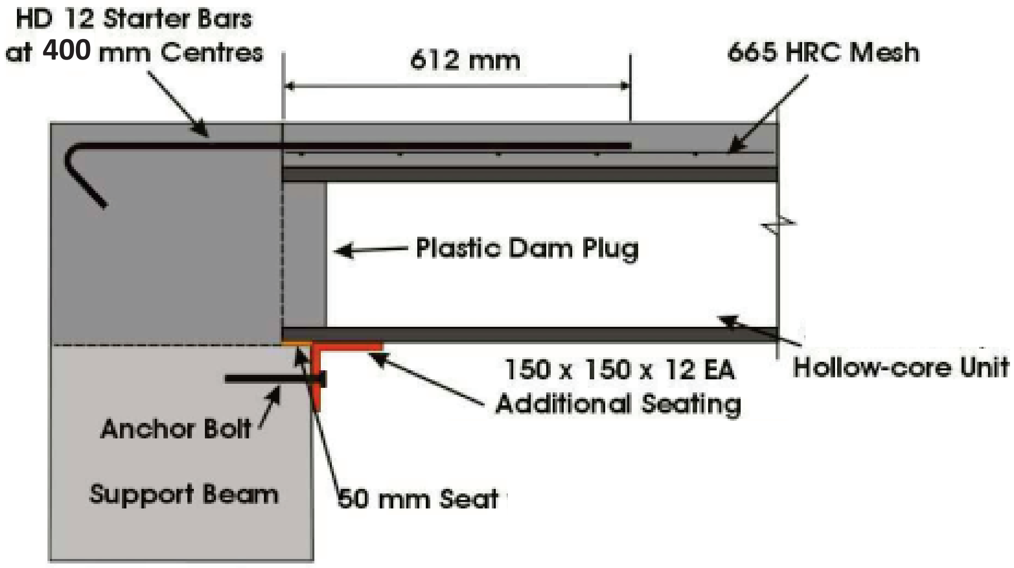
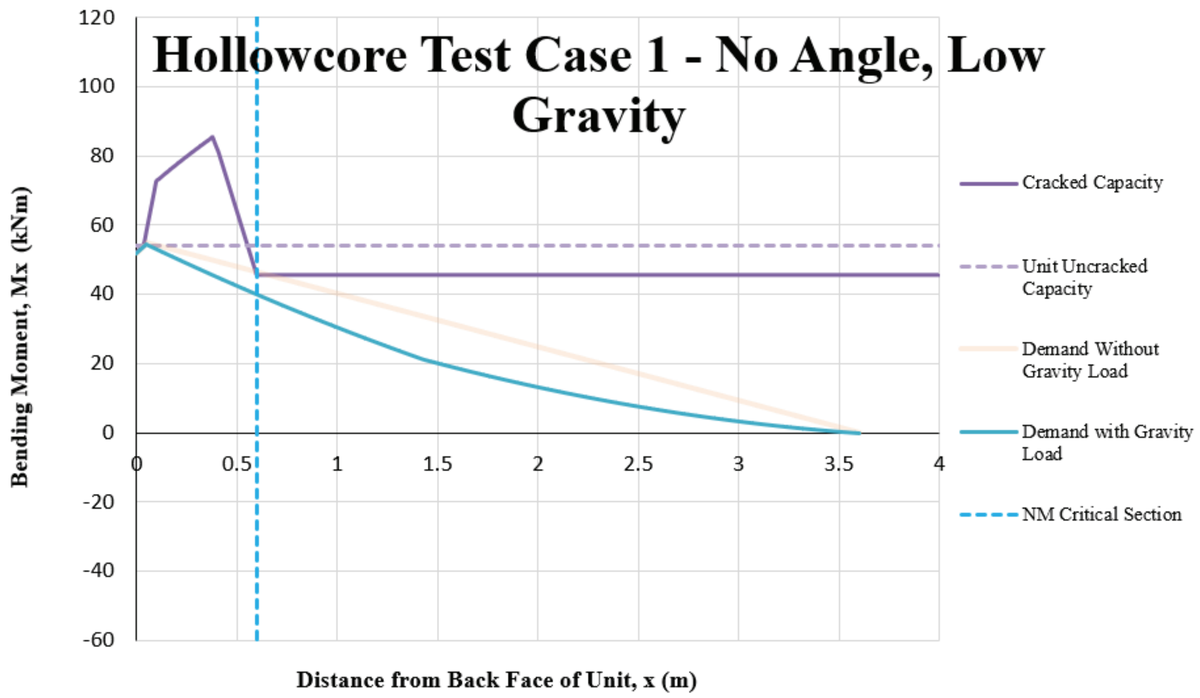


Figure B-1: Capacity-Demand Curve (Top) and Seating Connection Detail (Bottom – Sourced from Woods, 2008) for NMF Prone Case



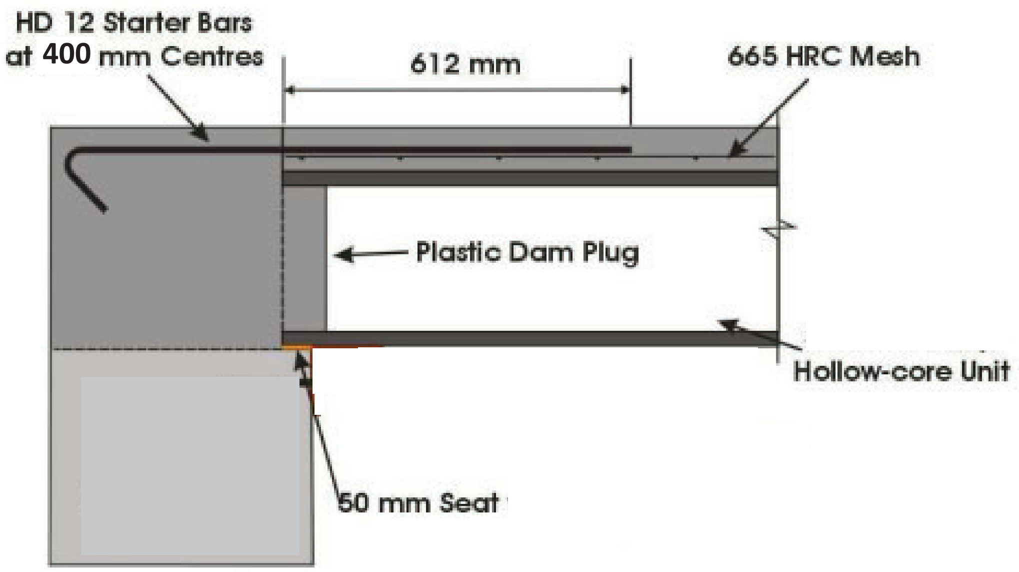


Figure B-2: Capacity-Demand Curve (Top) and Seating Connection Detail (Bottom – Sourced from Woods, 2008) for non-NMF Prone Case