

Experimental Investigation of Existing Hollowcore Seating Connection Seismic Behaviour Pre and Post Retrofit Intervention.

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ABSTRACT: In the recent past a number of issues regarding the seismic performance of typical existing hollowcore floor systems have been raised. The most concerning of these is the vulnerability to loss of vertical support of the floor system at the end floor to seating beam connection. This vulnerability arises due to incompatibilities between the floor system and intrinsic deformations of the neighbouring seismic frames.

In a previous contribution by the authors (Jensen et al 2006), a conceptual retrofit strategy for existing hollowcore seating connections was proposed. This paper provides an experimental validation of that strategy through quasi-static cyclic testing of alternative seating connection configurations, adopting varying seating lengths.

In general, unfavourable performance was exhibited by the existing seating connections, resulting in loss of vertical support of the hollowcore unit. In contrast, when additional seating and selective weakening retrofit approaches were implemented, a higher level of seismic performance leading to collapse prevention was achieved. In conclusion, issues and uncertainties associated with the evaluation of the likely failure mechanism, as well as the definition of an appropriate retrofit intervention are discussed.

1 INTRODUCTION

Post-earthquake reconnaissance and experimental investigations have identified a number of uncertainties regarding the seismic performance of suspended precast hollowcore floor systems when coupled with ductile seismic frame systems (Norton et al., 1994; Iverson and Hawkins, 1994; Holmes and Somers, 1995; Herlihy, 1999; Bull and Matthews, 2003; Liew, 2004; Matthews, 2004). These uncertainties are associated with the structural detailing and resulting behaviour of the connections between the floor and frame systems around the floor perimeter. The foremost of these uncertainties is maintaining vertical support of the one-way floor system at the end floor to seating beam connection during a seismic event.

The gravity load carrying capacity of the end seating connection can be jeopardised by incompatibilities between the intrinsic behaviour of the individual floor and frame structural systems. The frame behaviour of primary concern is the elongation of plastic hinges in the beams running parallel to the one-way floor system, and relative rotation between the floor system and the supporting end seating beam. Both result under the lateral drift of a ductile seismic resisting frame. The conflicting intrinsic floor properties are the one-way, brittle and unreinforced nature of the prestressed, concrete hollowcore flooring units. As a result of these incompatibilities, the end seating connection must accommodate both 'pull-off' and rotational deformation from beam elongation and seating beam rotation to maintain vertical support. The general connection philosophy adopted for typical existing seating connections has been shown to be deficient in both of these facets through insufficient seating ledges and higher than expected connection rotational fixity (flexural strength). The excess connection fixity results in flexure, shear and axial forces being imposed on the floor system which

were not considered in the original design of the connection. Consequently, the structural integrity and performance of the floor system, both in gravity support and lateral load transfer can be jeopardised.

This paper outlines an experimental investigation into the behaviour of existing hollowcore seating connections, followed by the validation of potential performance enhancing retrofit techniques for existing seating connections. Discussion is given regarding the outcomes of the experimental investigation and the complications associated with the implementation of the proposed retrofit techniques in practice.

2 TEST SETUP AND TESTED SEATING CONNECTION DETAILS

Four experimental tests were carried out using a single hollowcore unit and seating beam sub-assembly test rig as shown in Figure 1. The sub-assembly test rig imposed both the seating beam rotation and beam elongation ‘pull-off’ deformation demands on the end floor to seating beam connection. The deformations were imposed on the half span of hollowcore unit by hydraulic actuators and aimed to represent in-situ frame behaviour imposed on a floor system during a seismic event.

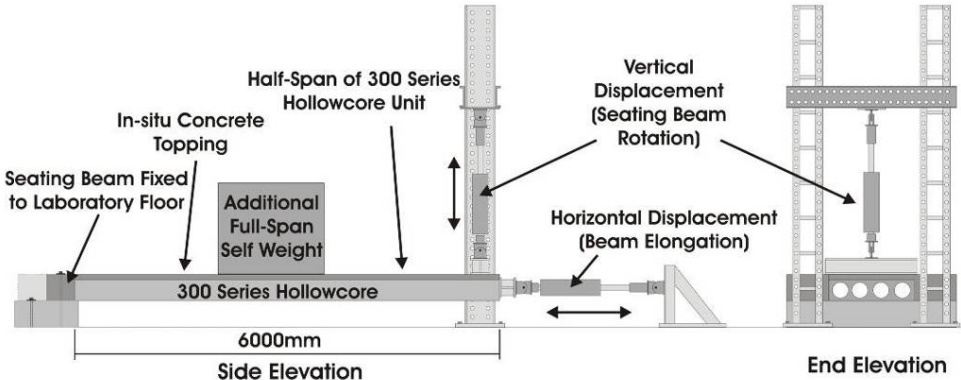


Figure 1 - Single hollowcore unit and seating beam sub-assembly test rig incorporating seating beam rotation and beam elongation deformation demands

The first three test specimens (HC1, HC2 and HC3) were benchmark specimens representing commonly adopted, existing hollowcore seating connection details (prior to Amendment 3 of NZS 3101:1995 of 2004) as shown in Figure 2 a), b) and c). The aim of this was to further develop the understanding of the seismic behaviour of existing seating connections and to provide insight for the development of appropriate retrofit techniques. The main variation from previous existing seating connection experimental tests was the implementation of the beam elongation ‘pull-off’ effects on the hollowcore unit and seating the hollowcore unit directly on the bare concrete seating ledge. Previous tests on existing hollowcore seating connection details seated the hollowcore unit on a mortar bedding material, which was thought to have substantial influence on the seating connection behaviour. The fourth test specimen (HC4) was a retrofitted specimen with the same initial existing details as HC3 (see Figure 3).

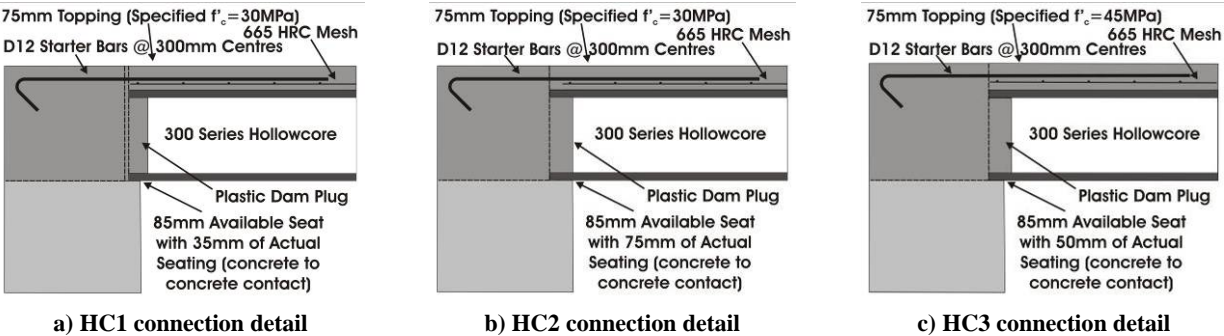


Figure 2 - Existing benchmark seating connection details

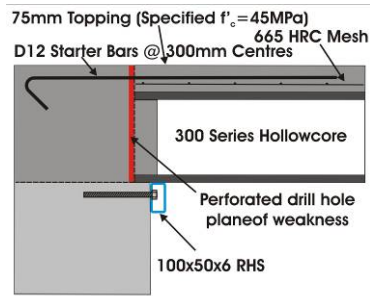
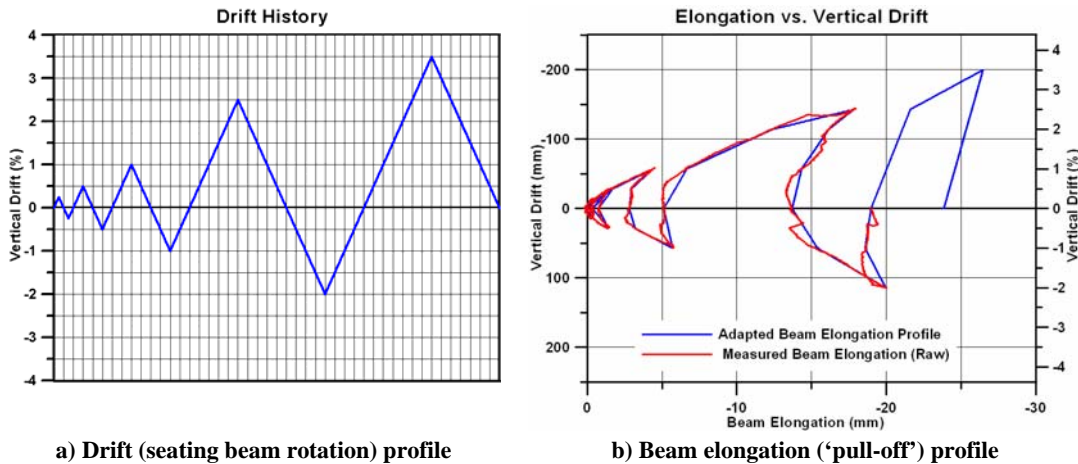


Figure 3 - Retrofitted seating connection detail (HC4)

The loading protocol adopted for the testing was adapted from that used by Matthews (2004) in a full-scale, three-dimensional hollowcore floor and frame super-assembly test. Matthews (2004) developed this protocol as an alternative to the traditionally adopted two reversing cycles of increasing ductility levels ('Park') loading protocol. The reason for this was it was thought that traditional approaches were too demanding for the assessment of existing structures. Matthews (2004) loading profile was based around a suite of non-linear time history analyses and was therefore more indicative of an actual earthquake than the harsher prototype verification tests typically used. The beam elongation ('pull-off') loading profile was inferred from the measured beam elongation from the Matthews (2004) super-assembly test. As a result, the nature and magnitude of the 'pull-off' effects imposed on the system matched the drift loading profile and was also more indicative of reality. Figure 4 illustrates the drift and beam elongation components of the loading protocol, this was the 'standard' test protocol later referred to in Section 3.



a) Drift (seating beam rotation) profile

b) Beam elongation ('pull-off') profile

Figure 4 - Drift and beam elongation loading components for the sub-assembly test specimens

3 EXISTING SEATING CONNECTION BEHAVIOUR (PRE-RETROFIT)

In general, the behaviour of the existing seating connection benchmark specimens was seen to be poor. Two of the three specimens (HC1 and HC3) lost gravity carrying capacity under the imposed drift (seating beam rotation) and 'pull-off' effects, resulting in collapse of the hollowcore unit. The observed behaviour of the three individual benchmark tests is described below and the observed failure mechanism summarised and illustrated in Figure 8.

3.1 HC1 seating connection test specimen behaviour

The behaviour of the HC1 benchmark specimen was characterised by high initial stiffness and strength, followed by sudden rupture of the interface between the end of the hollowcore unit and the seating beam. The rupture occurred at a drift level of approximately +0.25% (hollowcore unit soffit in tension). Following the rupture a pinned behaviour (very little flexural stiffness and strength) was observed in the positive drift direction (hollowcore unit soffit in tension). In the negative direction

(topping surface in tension) some residual stiffness and strength was maintained in the connection due to the presence of the starter bar reinforcement crossing the crack interface.

The crack interface was near vertical and ran from the edge of the provided seating ledge, up through the seated corner portion of the soffit of the hollowcore unit and through the cast in-situ concrete 'stubs' and topping (see Figure 5 c)). The nature and location of the crack interface was a result of a combination of trapped portions of the seated hollowcore unit soffit, spalling of the concrete seating ledge and rupture of the cast in-situ 'stubs' in the end of the hollowcore unit (see Figure 5 c) and d)) The crack interface negated the provided seating ledge, resulting in the vertical load carrying capacity of the connection being provided by only friction and interlock between the damaged end of the hollowcore unit and seating beam interface. Under increasing 'pull-off' demand, the hollowcore unit was seen to progressively slide down the crack interface until final collapse at a drift level of +3.0% and 'pull-off' in the order of 25 mm (see Figure 5 a) and b)). Due to the location of the crack interface and spalling of the existing seating ledge the elongation which caused collapse was less than the initial provided seating length.

Delamination of the in-situ concrete topping from the hollowcore unit was observed in the test specimen. The delamination was seen to be initiated early in the test by tensile strain penetration in the starter bar reinforcement under negative drift (topping surface in tension) stretching the topping. Figure 5 b) illustrates the delaminated portion of topping concrete suspended from the seating beam by the intact starter bars. Figure 5 d) shows the smooth surface on the top of the hollowcore unit where the topping has delaminated.

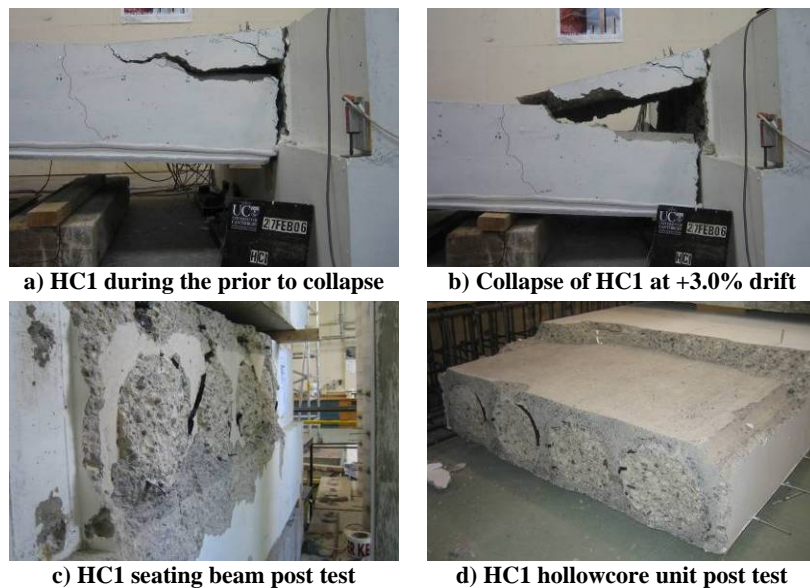


Figure 5 - HC1 experimental photos before and after testing

3.2 HC2 seating connection test specimen behaviour

The HC2 benchmark specimen behaved in a manner consistent with that of HC1 (see Figure 6 a)). High initial strength and stiffness was observed, followed by rupture of the hollowcore unit to seating beam interface at a drift of approximately +0.25%. However, due to the larger provided seating ledge (75 mm) no vertical drop of the hollowcore unit was observed and loss of vertical support was prevented up to a drift of +3.5% and an elongation of 20–25 mm. Further elongation was then applied to the hollowcore unit in the 0% drift position. Collapse of the hollowcore unit occurred under an elongation of approximately 55 mm, 20 mm less than the provided 75 mm seating length. The reason collapse did not occur during the initial standard loading was that the trapped portions of the hollowcore unit soffit and seating ledge spalling did not coincide along the entire length of the connection. As a result there were regions of seating ledge which remained effective and provided vertical support to the hollowcore unit (see Figure 6 b)). Figure 6 a) shows the location and nature of

the crack interface between the end of the hollowcore unit and seating beam at +3.5% drift and a ‘pull-off’ of 20–25 mm.

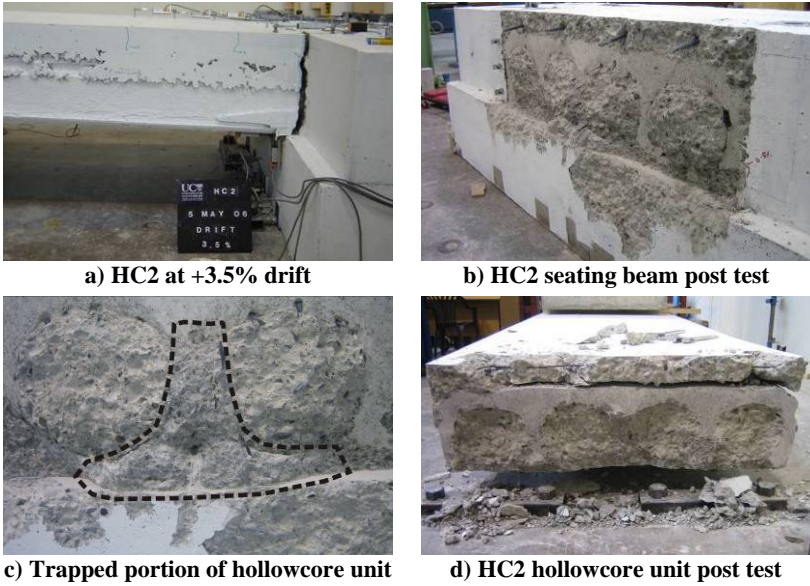


Figure 6 - HC2 experimental photos before and after testing

A large portion of the hollowcore unit, the full depth of the 75 mm provided seating length, was seen to be trapped on the seating beam (see Figure 6 b) and c)). This was likely due to the larger seating length (75 mm) providing higher restraint to the hollowcore unit soffit. This resulted in a higher positive connection flexural strength (hollowcore unit soffit in tension) and more demand imposed on the hollowcore unit. This is of concern as it indicates the potential for a flexure-shear failure (illustrated in Figure 9 a)) to occur in the hollowcore unit itself resulting in loss of vertical support. Delamination of the in-situ topping concrete was observed to a lesser extent than in HC1. This is illustrated in Figure 6 a) where there is no visible separation between the topping and hollowcore unit during testing. Figure 6 d) shows the extent of separation of the topping following completion of testing. At the completion of the standard testing procedure the starter bars were still intact, suggesting some extent of delamination had occurred during the test.

3.3 HC3 seating connection test specimen behaviour

The HC3 benchmark specimen exhibited rupture of the interface between the hollowcore unit and seating beam at a drift of approximately 0.25%. The nature of the rupture and location was consistent with both HC1 and HC2 tests. Collapse of the hollowcore unit occurred in a similar manner to HC1 at a drift level of -2.0% (topping surface in tension), under elongation of approximately 20 mm (see Figure 7 a) and b)). However, no delamination of the topping was observed and collapse occurred when three of the four starter bars ruptured. It was likely that the starter bars were supporting the hollowcore unit prior to collapse due to the large amount of spalling of the seating ledge. Figure 7 c) shows the underside of the specimen where the seating ledge has spalled away leaving the hollowcore unit suspended by the starter bars. The extent of the spalling of the unreinforced concrete seating ledge can be seen on the exposed seating beam in Figure 7 d). The HC3 benchmark specimen reached a much higher flexural strength prior to rupture when compared with HC1 and HC2. This was a result of the larger seating ledge and the higher compressive strength (compared with HC1 and HC2 tests) of the seating ledge concrete ‘stubs’ and topping concrete. This again illustrates the potential for large flexural forces to be imposed on the hollowcore unit and the likelihood of flexural-shear failure for this type of existing seating connection detail.

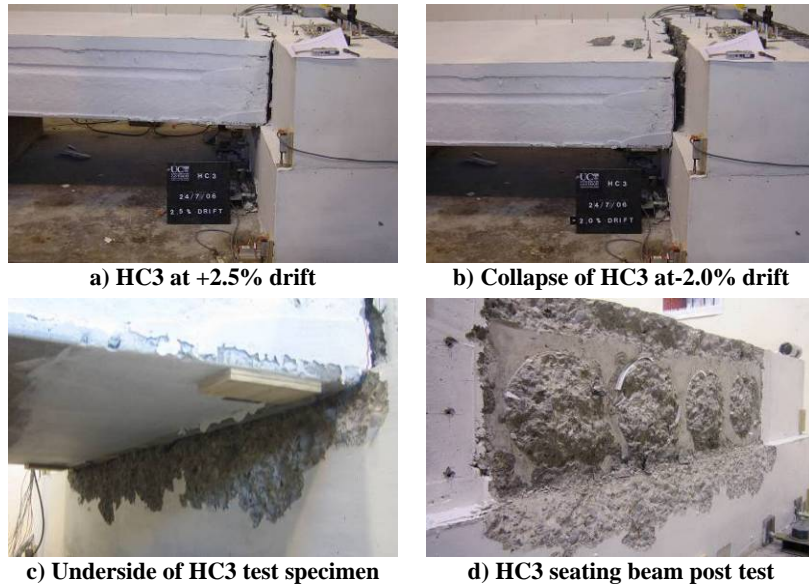


Figure 7 - HC3 experimental photos before and after testing

3.4 Loss of Seating Failure Mechanism (LOSD and LOS)

The generalised failure mechanism and seating connection behaviour observed in the three benchmark test specimens has been termed ‘Loss of Seating’. Two variations of the failure mechanism are described, that being Loss of Seating with and without Delamination (LOSD and LOS). The main cause of the failure mechanism is the combination of trapping of the seated portion of the hollowcore unit soffit and spalling of the unreinforced seating ledge (see Figure 8 a) and b)). As a result, the provided seating ledge is negated along the length of the seating connection. In the absence of topping delamination, the starter bars were observed to rupture due to tensile strain concentration at the crack interface between the hollowcore unit and seating beam (see Figure 8 b)). The experimental testing indicated that this failure mechanism is more likely to occur when the existing seating ledge is deficient.

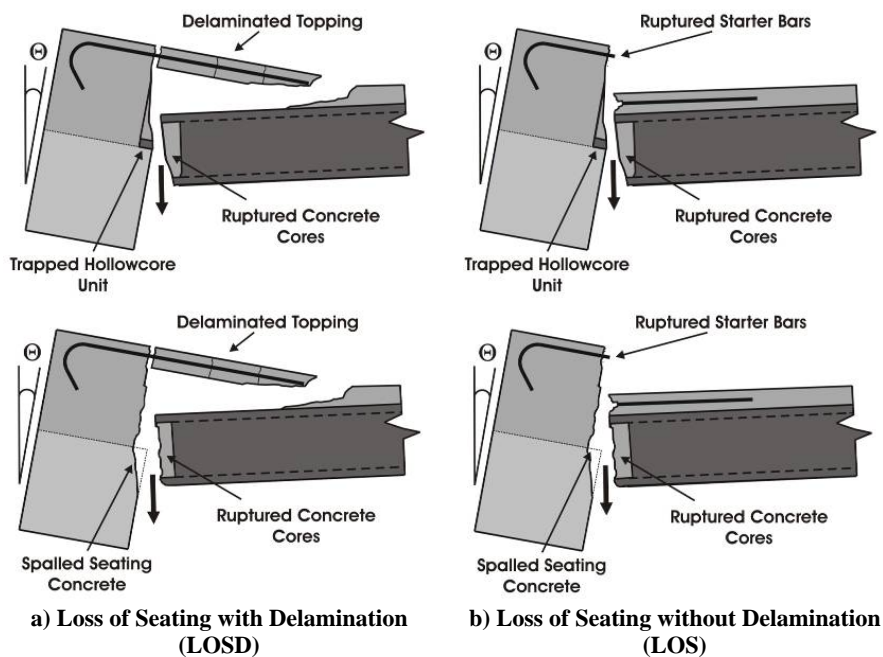


Figure 8 - LOSD and LOS failure mechanisms

The observation of the benchmark specimen behaviour highlights a number of concerns regarding the seismic performance of existing hollowcore seating connections:

- The unreinforced nature of the benchmark seating connections resulted in the rupture of the interface being unpredictable, without a clearly defined or calculable hierarchy of strength.
- The soffit of the hollowcore unit did not slide in the bare concrete seating ledge. As a result the strength and size of the seating ledge has a significant bearing on the overall positive connection strength.
- The provided seating ledge was negated due to the combination of trapped portions of the hollowcore unit soffit and spalling of the seating ledge. As a result the susceptibility of loss of vertical support of the hollowcore unit as a result of beam elongation ‘pull-off’ was heightened.
- The starter bar reinforcement cast into the in-situ seating beam and topping cannot be relied upon to provide vertical support to the hollowcore unit. This is due to either delamination of the in-situ topping concrete, or rupture of the starter bars at the crack interface between the end of the hollowcore unit and seating beam.

3.5 Alternative existing seating connection behaviour (FS and OFS)

In addition to the failure mechanism (LOSD and LOS) identified in this investigation, there are two alternative failure mechanisms previously identified by Matthews (2004) and Liew (2004). These are termed Flexure-Shear failure (FS) and Offset Flexure-Shear failure (OFS) as illustrated in Figure 9 a) and b). The FS failure mechanism was identified by Matthews (2004), which resulted in loss of gravity support of the one-way floor system through snapping of the hollowcore unit. This resulted from the overall seating connection strength (fixity) exceeding the strength of the hollowcore unit itself. The failure is exhibited by flexure induced diagonal shear cracking in the soffit of the hollowcore unit originating from the face of the seating beam as shown in Figure 9 a). The OFS failure mechanism was identified by Liew (2004) and is associated with seating connections which have excessive tie reinforcement placed in the ends of the hollowcore unit in the seating connection region. OFS is exhibited by similar failure behaviour as FS, only that the failure plane is offset by the length of the rigid reinforced cores within in the cores of the hollowcore unit.

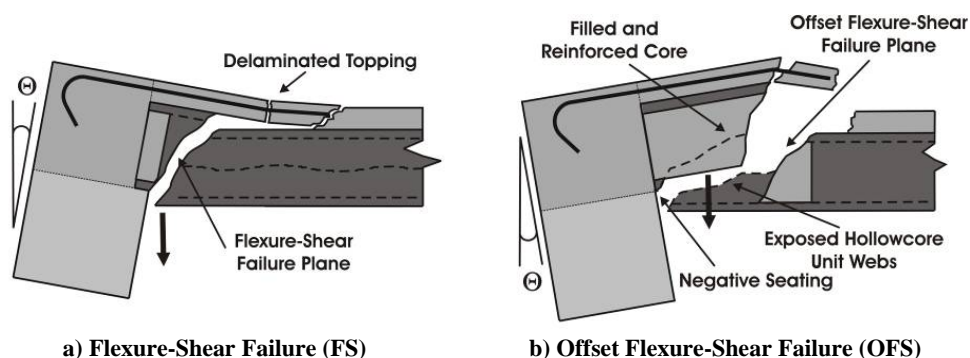


Figure 9 - Illustrations of FS and OFS Failure mechanisms identified by Matthews (2004) and Liew (2004)

3.6 Critical structural weaknesses for retrofit techniques to target

Two primary deficiencies in typical existing hollowcore seating connections were identified when considering conceptual retrofit techniques for the range of potential failure mechanisms. The first of these was the need to provide additional seating ledge to target LOSD and LOS type failure. In conjunction with this, reduction of the spalling of the existing seating ledge was seen as a secondary retrofit target. The second primary target was the need to reduce or control the flexural strength (fixity) of the seating connection to target FS and OFS type failures. The aim of this was to implement capacity design principles to protect the hollowcore unit through reducing the overall connection

strength.

4 EXISTING SEATING CONNECTION BEHAVIOUR (POST-RETROFIT)

4.1 HC4 test specimen behaviour

Two retrofit measures were implemented on the HC4 test specimen, which prior to retrofit was identical to the HC3 benchmark specimen detail. A steel rectangular hollow section (RHS) was fixed to the face of the seating beam, under the soffit of the hollowcore unit, providing an additional seating ledge (see Figure 10 a)). A secondary possible enhancement in behaviour was the application of the RHS to provide confinement to the existing unreinforced concrete seating ledge. The second retrofit intervention was the use of drill holes behind the hollowcore unit in a perforation pattern (see Figure 10 d)). The aim of this was to selectively weaken (Ireland et al, 2006) the interface between the hollowcore unit and seating beam, reducing the forces imposed on the hollowcore unit.

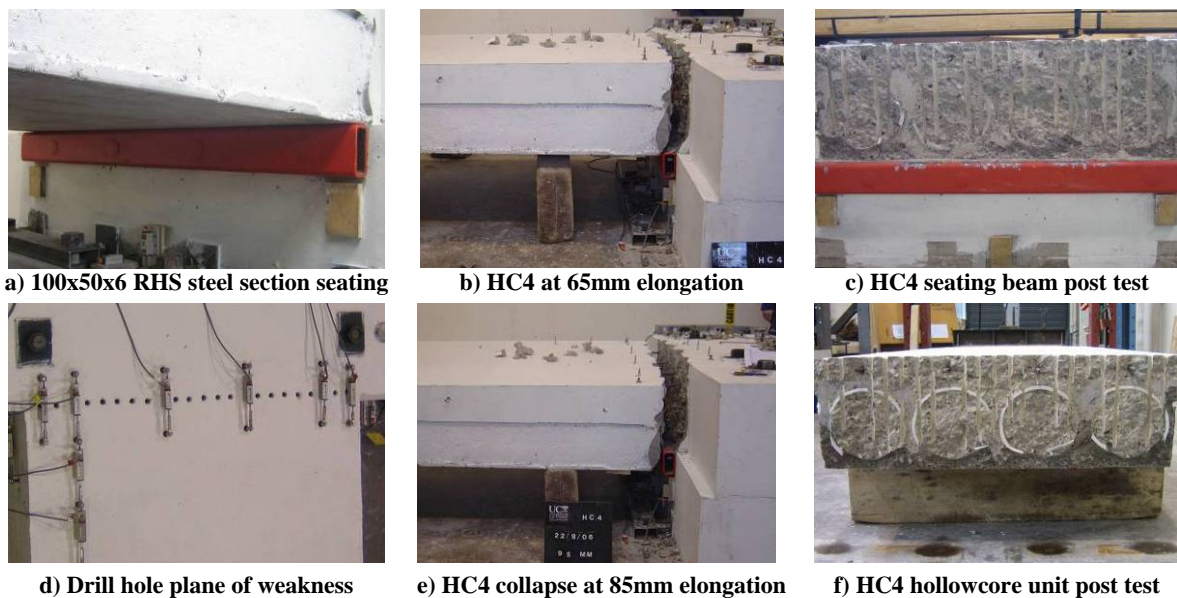


Figure 10 - HC4 test photos before and after testing

The HC4 retrofitted test specimen behaved in a manner consistent with the benchmark specimens until first rupture. At first rupture, the crack interface opened along the intended drill hole plane of weakness behind the hollowcore unit. This was illustrated by the exposed drill hole surfaces seen on both the end of the hollowcore unit and on the seating beam (see Figure 10 c) and f)). However, there were still portions of the soffit of the hollowcore unit trapped on the existing seating ledge, as shown in Figure 10 c). A reduction in peak positive flexural strength of approximately 30% was achieved as a result of the selective weakening intervention. This was less than desired and was likely due to the increase in restraint provided to the hollowcore unit soffit through confining the existing seating ledge, offsetting the weakening approach. This was further illustrated by the trapped portions of hollowcore unit soffit. The vertical load of the hollowcore unit was seen to be completely transferred to the RHS at a drift level of approximately +2.5%, under an elongation of 15 – 20 mm. A vertical drop of the hollowcore unit in the order of 2mm was observed as a result of the vertical load transfer to the RHS seating ledge. Due to the vertical load path provided to the hollowcore unit by the RHS collapse was prevented at the completion of the testing regime. Following the initial testing regime increasing levels of elongation were applied to the hollowcore unit in the 0% drift position. Collapse of the hollowcore unit occurred under an elongation of approximately 85 mm (see Figure 10 b) and e)), significantly greater than expected ‘pull-off’ effects in reality.

The confinement provided to the existing seating ledge by the RHS was seen to significantly reduce the extent of spalling of the existing unreinforced concrete seating ledge (See Figure 10 c)). A

negative aspect of the provided confinement was the increased restraint on the soffit of the hollowcore unit and potential increase in force actions imposed on the hollowcore unit. This highlights the need for care when using such a retrofit technique and the sensitive nature of existing hollowcore seating connections to external modification. In particular, the addition of external elements (seating) which obstruct the rotation of the hollowcore unit relative to the seating beam and elements which increase the overall connection fixity as shown by Liew (2004).

5 RETROFIT APPLICATION

5.1 Existing seating connection assessment uncertainty

The primary failure mechanisms identified and summarised in this investigation (including those identified by previous researchers) indicate that certain failure mechanisms are more likely to occur than others, given the nature of the seating connection details (the connection hierarchy of strength). For example, if the overall connection flexural strength exceeds that of the hollowcore unit, FS failure is more likely. If that is not the case and the seating ledge is deficient LOSD and LOS will be more likely, and if the cores of the hollowcore unit are reinforced OFS is more likely. This creates uncertainty in terms of identifying the likely failure mechanism due to the difficulty in determining the structural details of existing seating connections. The reason for this is the details which need to be identified are concealed within the seating beam, the hollowcore unit and the in-situ concrete topping (which make up the seating connection). This uncertainty is further compounded by the significant influence the concrete strength of the individual connection elements can have on the likely failure mechanism. This is also difficult to determine due to the unreinforced nature of the hollowcore units and often the overall connection detail. Therefore, the strength of the concrete making up the individual elements can control the flexural strength of the overall connection and hollowcore unit itself. However, the provided seating length is one of the potentially determinable detail aspects (by inspection of the underside of the connection), which could give some indication of the potential failure mechanism. This is the best indication available to indicate the likely failure mechanism. It is important however that this be inspected on site rather than read off the plan due to the high potential for variance between the two. The extent of this uncertainty can potentially be mitigated or avoided through the use of the selective weakening retrofit technique, which highlights the attractiveness of the approach.

6 CONCLUSIONS

Four single hollowcore unit and seating beam sub-assembly tests were carried out, which incorporated both seating beam rotation and beam elongation ‘pull-off’ deformation demands. The first three tests were benchmark specimens which aimed to further develop the current understanding of existing seating connection behaviour. The test specimens incorporated commonly adopted existing seating connection details with varying seating ledge lengths. The fourth test specimen was a repeated benchmark specimen with a retrofit intervention.

In general, poor performance was observed by the benchmark specimens, with two of the three tests collapsing due to loss of seating and therefore loss of vertical support of the hollowcore unit. The failure was a result of trapping portions of the seated soffit of the hollowcore unit on the seating ledge and spalling of the unreinforced concrete seating ledge. The combination of these facets formed a near vertical failure plane at the interface between the end of the hollowcore unit and seating beam. This negated the provided seating ledge and increased the seating connections sensitivity to beam elongation ‘pull-off’ effects. As a result, the elongation required to cause collapse was significantly less than the provided seating length.

The failure mechanism observed varied from those previously identified, which were a result of more significant damage to the hollowcore unit itself (rather than the seating ledge and interface between the hollowcore unit and seating beam region). As a result a suite of potential failure mechanisms were summarised based on various commonly adopted existing seating connection details (prior to

Amendment 3 of NZS 3101:1995 of 2004). Considering the potential failure mechanisms, a retrofit intervention was carried out which incorporated two retrofit techniques. A steel RHS section was fixed (bolted) to the face of the seating beam to provide additional seating ledge, and a plane of weakness introduced behind the hollowcore unit to reduce the connection fixity. Overall the retrofit intervention was successful with a 30% reduction in the connection flexural strength observed and collapse prevented. However, in reality there are uncertainties associated with identifying the likely failure mechanisms and implementing appropriate retrofit procedures. This is due to the concealed nature of the existing connection details and the significant effect the strength of the unreinforced concrete elements can have on the hierarchy of strength and likely failure mechanism.

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