# Conceptual Retrofit Strategy for Existing Hollowcore Seating Connections

2006 NZSEE
Conference

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**ABSTRACT:** Previous research regarding the seismic performance of existing precast hollowcore floor and ductile lateral frame systems has highlighted several behavioural uncertainties. In particular poor seismic performance due to deformation incompatibilities between the floor diaphragm and frame seismic resisting system have become apparent. Significant rotation and displacement demand on the floor systems due to frame beam elongation, seating beam rotation, and longitudinal perimeter vertical displacement have been identified as the main sources of undesirable damage. As a result the structural integrity at hollowcore seating and perimeter connection interfaces can be jeopardised, potentially leading to a partial or even complete floor collapse.

In this paper an overview of expected compatibility issues is given while providing suggestions for conceptual low-invasive retrofit strategies. Particular focus will be given to the experimental investigation on the vulnerability of and suggested retrofit solutions for hollow core-seating connections. The Quasi-static experimental testing procedure focusing on a series of as-built and retrofitted specimens, reproducing a hollowcore-to-seating-beam connection with traditionally adopted details will be presented. Both seating rotation due to the imposed lateral drift and beam elongation effects are simulated in the applied testing set-up. Simplified analysis and modelling aspects regarding the connection behaviour are discussed; expected damage and performance criteria associated with the alternative existing or retrofit solution are also tentatively indicated.

## 1 INTRODUCTION

Observed post earthquake collapse and extensive experimental investigation have highlighted significant uncertainties in the seismic performance of typical existing precast hollowcore floor diaphragm systems when coupled with ductile seismic resisting frames (Norton et al. 1994; Matthews et al. 2003). A poor combined structural response results from the conflicting intrinsic behaviour of the two individual structural systems; that being seating beam rotation, frame beam elongation, and longitudinal perimeter vertical displacement of the frame systems; and the stiff, brittle nature of hollowcore floor units, in addition to the lack of any transverse reinforcement.

The behavioural conflicts occur in the rigid, monolithic seating and perimeter connection regions between the two systems and exhibit themselves through web splitting, topping delamination, loss of hollowcore unit support locally or over entire floors, and general damage causing inelastic action in and around the floor perimeter. Consequently the structural integrity and performance of a buildings structural system, both in gravity and lateral load facets can be jeopardised or completely lost both locally and globally within the floor plane. Research has since shown that through a number of simple structural modifications to the seating and longitudinal perimeter connections much higher levels of performance can be achieved by such systems (Lindsay et al. 2004; MacPherson et al. 2005). Particularly, alternative seating connections have been tested in a full-scale floor and frame 3-D super-assembly, showing a higher performance when compared with a typical existing seating connection. As a result two acceptable solutions for hollowcore seating connections have been amended within the NZ Standard (NZS3101:1995, Amendment 3 2004) for use in new construction practice. However, there has been little research carried out investigating retrofit procedures for existing buildings designed prior to the implementation of amended connection details. This paper outlines the research motivation and intent of an ongoing research project at the University of Canterbury to investigate possible retrofit strategies. Discussion is given regarding the issues and ideas surrounding the development of a low-invasive retrofit strategy for existing hollowcore seating connections.

## 2 SEATING CONNECTION INCOMPATIBILITY ISSUES

### 2.1 Seating Beam Rotation

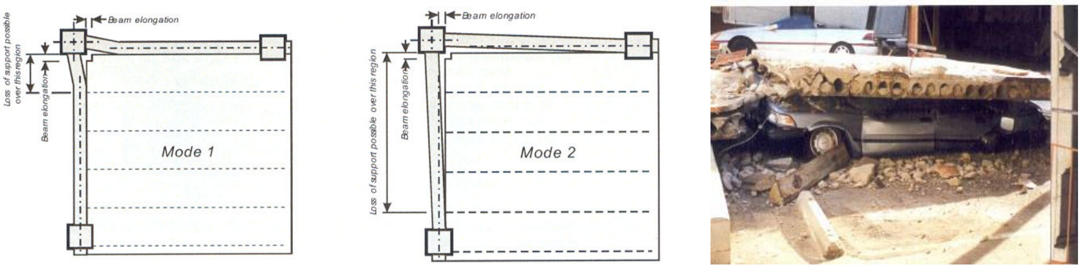
Interaction of the floor diaphragm and seismic frame system can result in an undesired snapping action in the rigid monolithic seating connection region due to the beam rotation demand imposed on the brittle hollowcore floor system. Due to excessive fixity in the seating connection detail the rotation of the seating beam is directly imposed on the hollowcore unit rather than the unit sliding as initially assumed (Matthews et al. 2003) (Fig. 1a). This snapping action is detrimental to the hollowcore units due to the brittle nature of the units and absence of any transverse reinforcement. As a result of the inability of the hollowcore floor diaphragm system to sustain the induced actions the webs of the hollowcore split in a diagonal pattern up through the unit end region and horizontally along the mid section of the web. This can lead to partial or full collapse of individual units and, potentially, of complete floors (Fig 1).

a) b) c)

Figure 1 – a) Hollowcore snapping action (Matthews 2004); b) web splitting Meadows Apartment car park, Northridge 1994 (Norton et al. 1994); c) seating region damage Matthews test (Matthews 2004)

### 2.2 Beam Elongation

Beam elongation in the frame beams spanning parallel to hollowcore units result in a “pull-off” effect on the units. The continuous, monolithic connection between the two outside units and frame beams results in any elongation occurring in the beams being imposed on the two outside units and possibly tracked further into the floor and interior units (Fig. 2a). The consequence of this is the seating support of the units can be jeopardised as the units can be pulled off the provided seat if excessive elongation is experienced (Matthews et al. 2003).

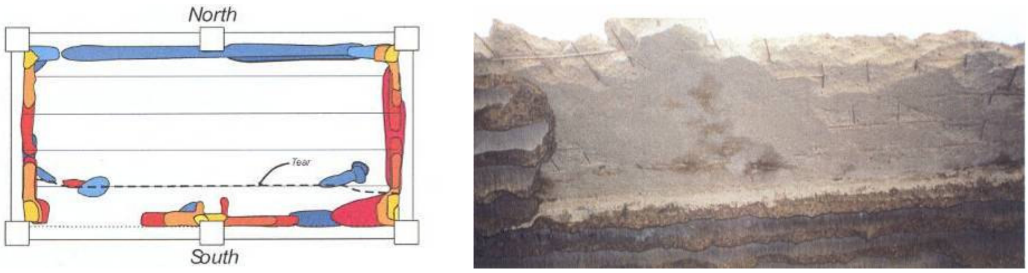


a) b)

Figure 2 – a) Loss of seating failure modes (Matthews 2004); b) loss of seating Meadows Apartment car park, Northridge 1994 (Norton et al. 1994)

### 2.3 Topping Delamination

Topping delamination is a second order effect as a result of the inelastic actions which occur in the topping due to incompatibilities in seating and perimeter connection regions (Fig. 3a). The danger of topping delamination is the loss in vertical support redundancy of the units and the disruption in lateral force distribution from the floor plane to lateral load resisting systems (Herlihy 2000; Matthews 2004). Delamination can result in loss of integrity of gravity and lateral load resisting structural systems.

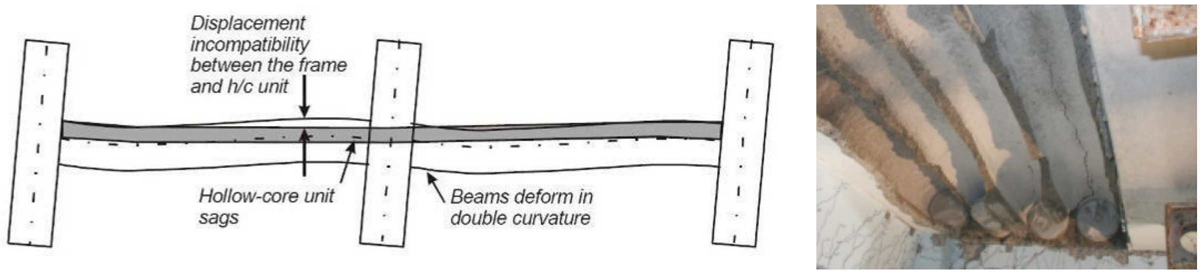


a) b)

Figure 3 – a) Delamination regions from Matthews test (Matthews 2004); b) delamination Meadows Apartment car park, Northridge 1994 (Norton et al. 1994)

### 2.4 Vertical Displacement Incompatibility

Vertical displacement incompatibility is a problem associated with the seating connection due to the two outside units being fixed by both seating and longitudinal perimeter connections. Previous research has shown interaction between vertical displacement incompatibility and seating connection rotation incompatibility is important as the behaviour of the seating connection can affect the extent of incompatibility along the longitudinal connection (Taylor 2004; MacPherson 2005). Vertical displacement incompatibility occurs due to the differing deformation modes of the frame and floor systems; the frame beams deform in double curvature where the hollowcore units are designed to act in a simply supported fashion and sag in single curvature (Fig. 4a). The hollowcore units are forced to deform with the frame beams due to the continuous monolithic connection between the two systems; for which the hollowcore units are not designed (Matthews et al. 2003). Significant damage can result in the form of web splitting in the hollowcore units and topping delamination.



a) b)

Figure 4 – a) Vertical displacement incompatibility along longitudinal perimeter connection; b) web splitting of first unit adjacent to longitudinal perimeter connection (Matthews 2004)

## 3 DEVELOPMENT OF ALTERNATIVE SEATING CONNECTIONS

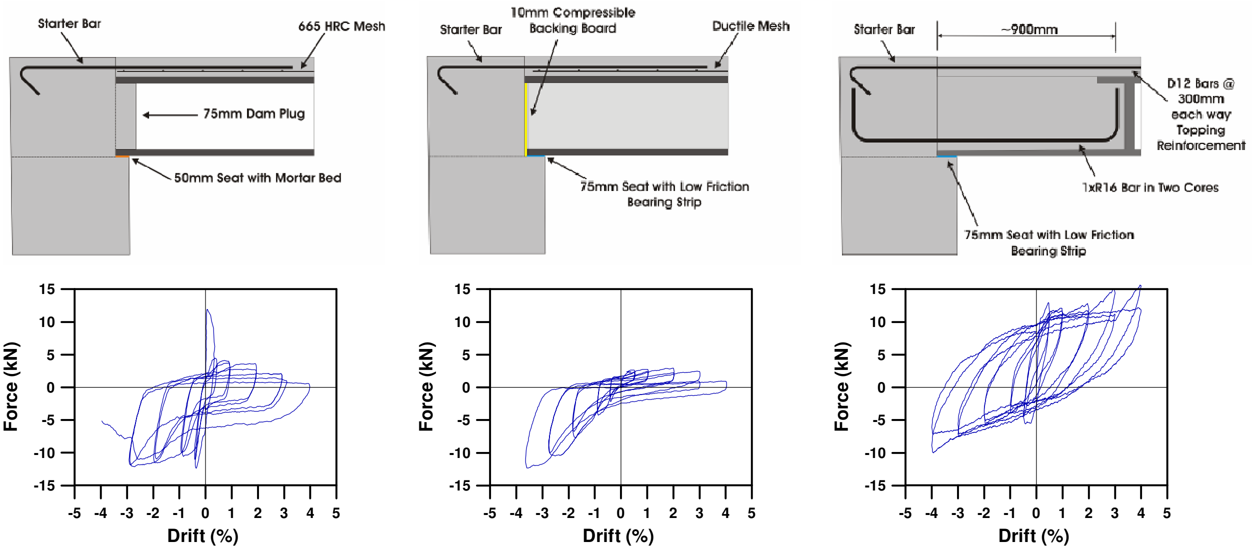
### 3.1 Connection Modification Approaches

To improve the seismic performance of precast hollowcore floor diaphragm systems a series of modified seating connection details were developed by the Technical Advisory Group for Suspended Concrete Floors (TAG) (TAG 2002), which targeted the critical seating connection incompatibilities. Two generalised approaches were observed in the modified connections: either to isolate the units from the seating beam by releasing the rotational degree of freedom; or, alternatively, to reinforce the end region of the unit, increasing the robustness of the unit, confining any inelastic action to the joint interface between the seating beam and reinforced end of the unit. Both approaches involved increasing the seating length and incorporating a low friction bearing strip on the seat to stop the soffit of the units binding on the seat.

### 3.2 **Advanced Performance of Modified Connections**

Following the testing of a typical existing seating connection detail, N1, in a full scale frame and hollowcore floor super-assembly (Fig. 5a), two modified connection details have been tested. The first of these modified connections tested, N2, was a simple type connection with a compressible backing board, an increased seating and a low friction bearing strip (Fig. 5b). The backing board aimed to prevent any topping concrete entering the cores of the unit to isolate the end of the unit from the seating beam and reduce the compression forces on the unit ends. Only the topping and starter bars cross the joint interface between the two elements. The second of these connections, N3, had the same seating and low-friction bearing strip as N2, however was more rigid with two of the four cores (300 series unit) reinforced with a bar passing along the bottom of the core (Fig. 5c). Topping concrete was prevented from entering the remaining un-reinforced cores as with N2. Both connections performed well, reaching much higher levels of displacement demand than the typical existing connection detail, N1, and have been included in Amendment 3 of NZS3101:1995. Concern regarding the simple type connection was raised due to possible susceptibility to loss of seating under excessive elongation. The absence of reinforcement in the cores results in no redundancy in the support mechanism, as is the case of the fixed type connection with reinforcing tying the hollowcore unit into the seating beam.

Figure 5 also shows the typical hysteretic behaviour of alternative seating connection details, representing either existing or modified solutions tested at a sub-assembly level, prior to implementation in the full scale super-assembly test-unit (Bull and Matthews 2003, Trowsdale 2004). Valuable information regarding the local performance and efficiency of the connection can be gathered when comparing the hysteretic response. What may be conceived as ideal hysteresis behaviour (i.e. a fat loop typical of a monolithic reinforced concrete connection with little or no strength or stiffness degradation) may not necessarily imply that the corresponding solution is the most effective. The simple N2 connection shows for example hysteretic behaviour with stiffness degradation and pinching effects, thus far from what may be generally considered ideal. However the physical performance of the connection was very satisfactory, with sufficient rotational freedom preventing positive rotation demand being transferred to the unit.



a) b) c)

Figure 5 - Development of improved seating connections and hysteretic behaviour: a) Existing (N1) (Matthews 2004; Bull and Matthews 2003); b) NZS3101 Amendment 3 (N2) (Lindsay et al. 2004; Bull and Matthews 2003); c) NZS3101 Amendment 3 (N3) (MacPherson et al. 2005; Trowsdale 2004)

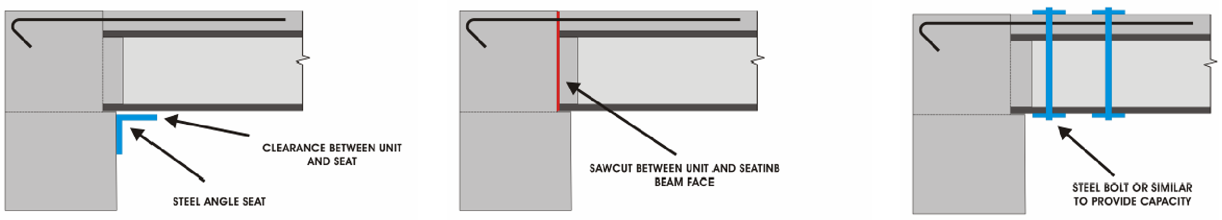
## 4 PROPOSED RETROFIT STRATEGY

### 4.1 General Retrofit Philosophy

The proposed retrofit strategy aims to emulate the behavioural characteristics exhibited by the amended connection details and bring existing connection performance closer to the amended connection levels of performance. The philosophy behind achieving this is to consider the methods which were used to improve the individual aspects in the amended connections and how similar strategies could be introduced to existing connections through in-situ retrofit techniques.

### 4.2 Individual Retrofit Concepts

To emulate the increase in minimum seating length specified in Amendment 3 of NZS3101:1995, the addition of a steel section or similar by means of fixing additional seating to the side of the seating beam has been suggested (Matthews 2004; Liew 2004) (Fig. 6a). A retrofit connection of this nature has been tested but with limited success due to fixing the steel section tightly against the unit soffit creating a clamping effect and shifting the snapping problem further into the precast flooring unit. In addition, the negative moment demand increase due to the clamping of the unit soffit resulted in "breaking the unit's back". To avoid this it has been suggested that the seat be set below the unit with clearance to avoid the clamping effect (Liew 2004). Using this as a sole retrofit technique would still leave doubt as to whether the un-reinforced angular portion of the unit (post-web splitting) supported on the additional steel seat would be sufficient to support the unit. In addition this type of approach relies on the unit snapping and therefore would require replacement. If further measures are taken more desirable performance may be achieved (primarily preventing the unit from snapping) under target seismic intensity levels, according to a performance based design approach. Appropriate measures may include further retrofit concepts (Fig. 6b and Fig. 6c) or more specific seating details able to provide seating support while accommodating the rotation demand.



a) b) c)

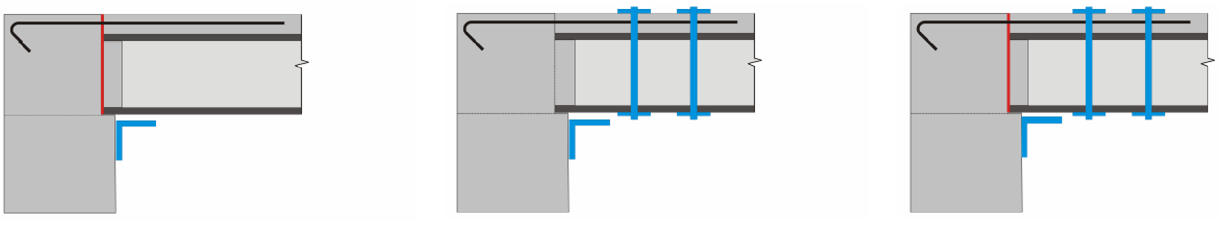
Figure 6 - Individual retrofit concepts: a) R1; b) R2; c) R3

To reduce the fixity and rotational actions imposed on the unit a selective weakening approach (Ireland et al. 2006) could be implemented, by introducing a separation between the unit and the face of the seating beam, as was the purpose of the compressible backing board used in the simple N2 amended seating connection (Fig. 6b). A vertical saw-cut could be made along the length of the joint interface behind the end of the unit to achieve this. This may introduce practicality complications in both implementing the cut and reinstating lateral force transfer through the topping region of the connection. However the resulting performance enhancement will likely be significant as a result of isolating the unit end from the seating beam.

To increase the robustness of the end region of the unit, replicating the reinforced cores of the second amended connection (N2), additional restraining force would need to be provided externally to the in-situ units. This could be achieved by drilling through the cores of the unit and inserting bolts or similar tensile elements which are fixed to the soffit of the unit and the upper surface of the unit or topping (Fig. 6c). This could potentially provide sufficient capacity to resist the snapping action imposed on the unit by the rotation of the supporting beam (the "seat"). When using this type of approach care must be taken not to over reinforce the connection region and ensure any inelastic action occurs in a controlled manner in the discrete connection interface between the end of the precast unit and the face of the supporting beam. If this is not achieved the problem may only be shifted further along the hollowcore unit as the reinforced region simply acts as a stiff cantilevered extension of the seating beam (Liew 2004; MacPherson et al. 2005). A secondary advantage of this component, if fixed to the topping, is the potential clamping force on the topping will improve topping to unit bond in the region of the connection helping to prevent delamination. This is a potential performance bonus which could significantly improve the performance of the structural system through maintaining lateral force transfer capability between floor diaphragm system and lateral load resisting frame system.

### 4.3 Combined Retrofit Strategies

Each of the individual retrofit concepts will not likely provide a comprehensive retrofit strategy individually, but rather be adopted in combination. Individual retrofit solutions may not be suited or applicable depending on the nature of individual seating connections which may also govern the retrofit strategy combination used.



a) b) c)

Figure 7 – Combined retrofit concepts; a) R12; b) R13; c) R123

### 4.4 Performance Criteria

Performance evaluation of the tested retrofit strategies will consider the local performance of the seating connection and the effect on associated structural elements, connections, and global performance of the building. Comparisons will be made between the retrofitted connections, a control specimen tested within this research program and a set of previously tested solutions adopting either existing or improved seating details. In addition, effects of the retrofitted connections on the global building behaviour will be examined analytically; as mentioned and observed in previous research, ideal local connection behaviour may not necessarily result in desirable global behaviour. The numerical model will incorporate each of the seating connections hysteretic behaviour into a non-linear lumped plasticity frame and floor model to investigate the more global behavioural effects of each retrofit concept (Fig. 8), particularly the effect each connection has on the incompatibility along the neighbouring longitudinal perimeter connection.

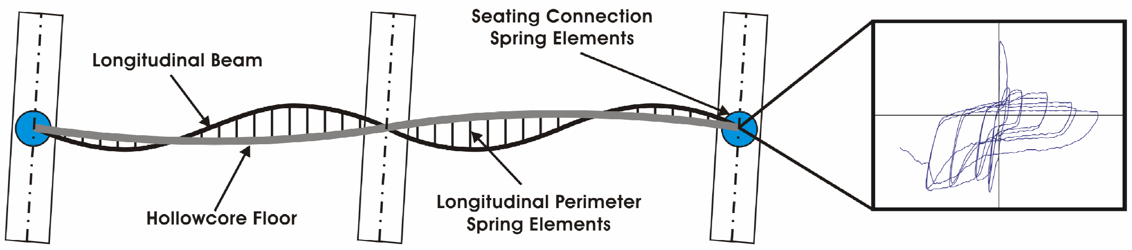


Figure 8 - Frame and floor analytical model to investigate displacement incompatibility (Taylor 2004; Bull and Matthews 2003)

## 5 PRACTICAL RETROFIT APPLICATION

### 5.1 Implementation and Practicality

For retrofit strategies to be industry applicable both the retrofit concept itself and the installation of the retrofit must be low-invasive and practical. It is important the working status of the building can be maintained during the implementation with minimal interruption to building occupants. As the retrofit concepts proposed involve only small hand placed structural additions, this will only affect the small perimeter connection region of floor space. Therefore minimal invasiveness of the implementation should be achievable. The process will also be able to be carried out in stages over individual floors, sides of floors or even frame bays, further simplifying the installation process and minimising interruption.

Complications with the installation of individual retrofit concepts may arise, particularly with the saw cut at the seating beam-hollowcore interface. It is important that the lateral force transfer capabilities of the connection are reinstated following the cut. In order to reinstate lateral force transfer capability any reinforcing and concrete cut from the topping region of the connection will have to be replaced or previously provided load paths replicated in some manner. Achieving this may complicate the retrofit procedure, particularly if replacing sections of starter bars and topping concrete are necessary.

The invasiveness of the additional bolt elements which protrude from the floor will be a concern depending on the use of the building. However, this may be avoided by recessing the bolt connections into the existing topping; or alternatively if sections of topping are replaced bolts can be fixed directly to the surface of the unit and covered by new topping reinstating the original floor surface. Recessing bolts in existing topping will be aided by the fact that the topping concrete will often be thicker than intended in this region due to the hogging of the hollowcore units and the flat nature of the finished floor surface, resulting in accumulating concrete at the end regions of the units.

### 5.2 **Connection Analysis**

For retrofit strategies to be applied without arbitrarily choosing the structural modification elements, a simple hand type approach will be required to analyse the existing connection to determine additional required capacity. Currently fundamental reinforced and prestressed concrete principles have been used to assess the connection strengths. However due to the existing nature of the connections and the fact that the hollowcore units are prestressed and the combined topping and hollowcore unit diaphragm is a composite section time effects may have a significant bearing on the connection. Time effects such as creep, prestress relaxation and stress transfer between the unit and topping will have a significant bearing on the connection's strength capacity (Fenwick et al. 2005). Fenwick et al. (2005) suggest a series of calculation approaches which focus more specifically on such aspects and attempt to understand this behaviour and estimate the connection capacity considering this. It is expected that the experimental results from this research investigation will complement and further develop the understanding of floor-frame interaction issues. Furthermore, simplified analytical methods will be validated and refined.

## 6 **EXPERIMENTAL IMPLEMENTATION**

### 6.1 **Test Rig**

A sub-assembly test rig comprising a single hollowcore unit seated on a short length of seating beam will be used to experimentally investigate the seating connection behaviour (Fig. 9). The sub-assembly is derived from the 3-D super-assembly frame and hollowcore floor system used at the University of Canterbury. Direct comparison can be made between the simplified sub-assembly tests and the more complicated super-assembly tests. The sub-assembly incorporates both seating beam rotation and longitudinal beam elongation effects in order to replicate the full specimen actions experienced by the hollowcore units in reality. It has been shown that the sub assembly is capable of reasonable replication of the full super-assembly behaviour at the floor to beam connection with the omission of any three dimensional effects (Liew 2004; Matthews 2004; Trowsdale 2004; MacPherson 2005). Because of this good agreement between the sub- and super-assembly results, and that the seating connection is of primary interest, the use of one dimensional units is seen as an acceptable simplification in order to reduce cost and increase the frequency of tests.

The loading protocol to be used will be adapted from Matthews (2004) super-assembly loading protocol. This protocol was developed by Matthews (2004) following a non-linear time history investigation into the response of typical reinforced concrete frame buildings excited by a suite of earthquake records. This protocol was adopted rather than the traditional two reverse cycles of increasing ductility due to the existing nature of the structure; hence the conservatism in the traditional method used for new structures is inappropriate. To overcome uncertainties related to the theoretical prediction of the elongation component of the loading protocol, measured elongation values corresponding to the Matthews (2004) test will be adapted and used. The testing program consists of four tests: a control specimen followed by three retrofit solutions

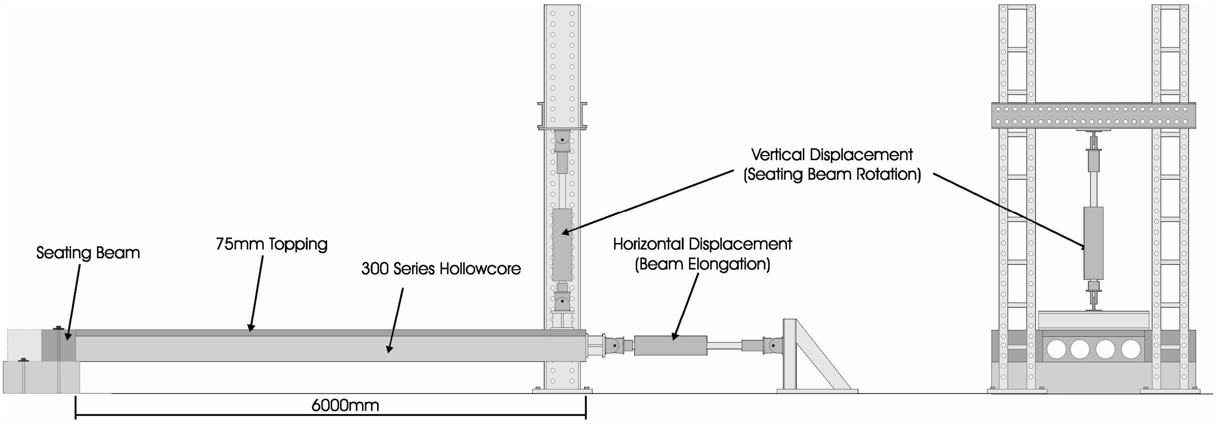


Figure 9 - Test rig setup

## 7 CONCLUSIONS

Experimental investigations have shown significant structural weaknesses in existing (designed prior to Amendment 3 NZS3101:1995) hollowcore floor diaphragm and ductile reinforced concrete frame systems. This is due to the intrinsic deformation incompatibilities which occur at the connection regions between the individual structural systems. The development of alternative connection details has considerably improved the behaviour of these systems for new construction; however there are no proven successful retrofit procedures for the existing stock of buildings. A pragmatic low-invasive retrofit philosophy has been presented based on techniques which target the observed weaknesses through replicating the strategies successfully implemented in the amended connections. Issues and possible solutions regarding practicality and implementation of the proposed retrofit strategy have been briefly discussed.

## ACKNOWLEDGEMENTS

The financial support provided by the NZ Foundation for Research, Science and Technology through the FRST Research Program “Retrofit Solutions for NZ” is gratefully acknowledged. The material support provided by Firth Industries Ltd and Stresscrete is also kindly acknowledged.

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