Lessons learned from the first building retrofit adaptation of ReCast

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ABSTRACT

This paper presents the collaborative and successful design and implementation of the first comprehensive retrofit works to upgrade the seismic resilience of a 1980s multistorey reinforced concrete frame building with hollow-core floors using new guidance from the ReCast Floors research programme.

The building features a 16-storey tower supported on a 4-storey split level podium. Assessment of the existing tower, completed in accordance with The Seismic Assessment of Existing Buildings ('The Guidelines') (MBIE et al., 2017), showed structural weaknesses related to incomplete diaphragm load-paths and hollow-core brittle failure mechanisms.

The project team's objective was to achieve a building rating of at least 100% NBS in accordance with The Guidelines, while incorporating key findings from the ReCast research programme. This industry-first approach required novel design solutions, necessitating the development of a new design philosophy and acceptance criteria related to drift limits, diaphragm stiffness and acceptable diaphragm load-paths, which are presented and discussed in this paper. The design philosophy had to address challenges typical of 1980s practice: which emphasized highly ductile structural systems, now understood to contribute to brittle hollow-core failure modes and separation of perimeter moment-resisting frames from diaphragms. The adopted design philosophy used supplemental damping devices to reduce building drifts and accelerations, reducing the extent of the existing structure which could not meet the acceptance criteria. Remaining challenges could then be addressed using targeted hollow-core retrofit and steel straps tying across the building to complete diaphragm load-paths and limit frame separation from the building.

1 INTRODUCTION

This paper documents the first application of ReCast Floors research guidance (Brooke et al, 2022) to a real-world seismic retrofit project, demonstrating how those research findings were translated into practical solutions for 80 The Terrace (80TT), a 1980s reinforced concrete (RC) two-way moment frame building with hollow-core floors located in Wellington (Figure 1).

The project team consisted of a collaboration between McKee Fehl Constructors (MFC) as the Main Contractor, Holmes as the Engineer, and Cheops Holdings as the Building Owner. Early Contactor Involvement (ECI) was instrumental for refining retrofit designs to achieve efficient, generalised details that could effectively interface with the existing structure – while accounting for the challenges posed by 80TT's specific existing structural and non-structural detailing. 80TT features a 16-storey tower supported on a 4-storey split level podium. This paper focusses on the first 12 storeys of the tower (Figure 2). This middle portion of the building is typical of 1980s building stock in Wellington, so presents an opportunity to share learnings that may be applied to other similar buildings requiring retrofit.

2 ASSESSMENT OF THE EXISTING STRUCTURE

Assessment of the existing tower completed in accordance with The Seismic Assessment of Existing Buildings ('The Guidelines') showed structural weaknesses related to incomplete diaphragm load-paths and hollow-core brittle failure mechanisms (Figure 3).

For the existing tower floor diaphragms, the identified incomplete load-paths were characterised into two components:

- The first was missing (or unreliable) tension ties due to expected rupture of non-ductile mesh reinforcement in the insitu concrete floor toppings when subjected to seismic demands (Fenwick et al., 2010), and brittle connection of the internal beams into the perimeter moment frame. Non-ductile mesh is typical for the era of construction with hollow-core flooring systems and has the outcome that the existing mesh can rarely be relied on to resist tension demands. In the case of 80TT, ductile saddle starter bars were not present across interior beams, meaning this was an additional weak zone for the tension load-path.

Figure 1: 80 The Terrace (prior to retrofit)

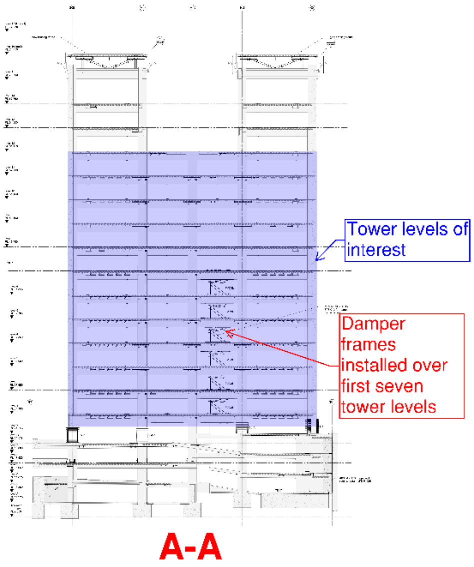


Figure 2: Elevation showing tower levels of interest

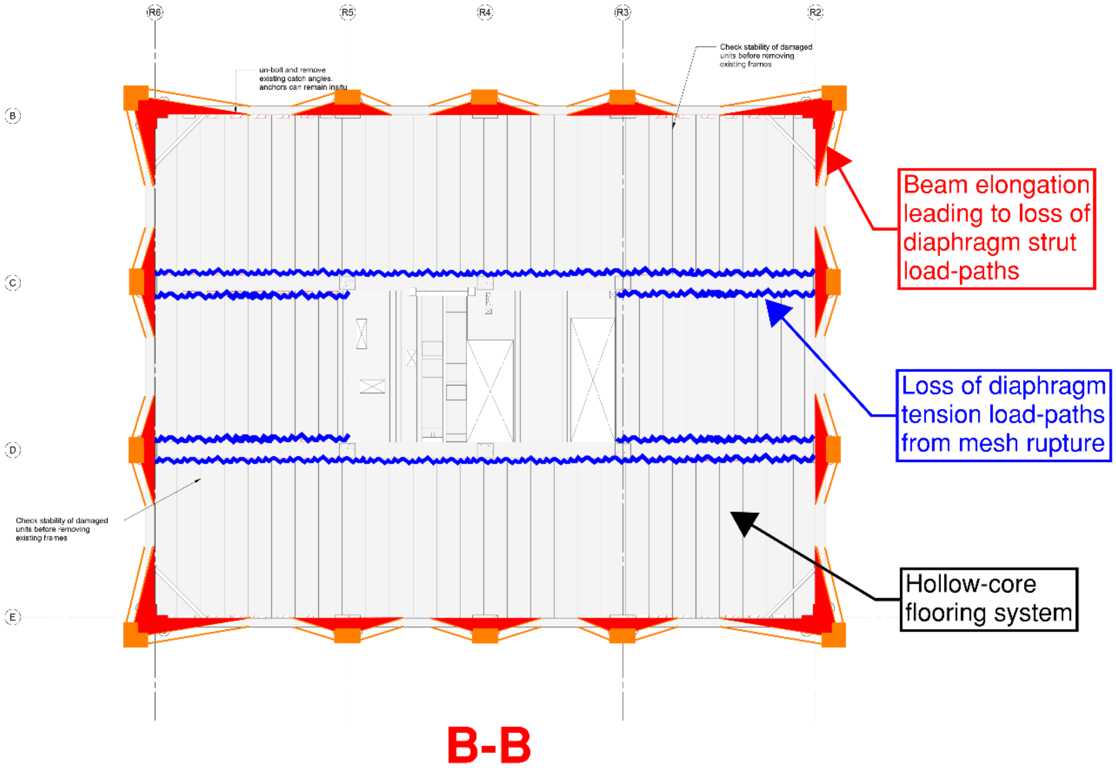


Figure 3: Plan view of a typical tower floor annotated with seismic behaviour requiring retrofit

- The second was loss of compression struts into the lateral load resisting perimeter frames due to beam elongation (the process of reinforced concrete beams accumulating plastic strain under reverse cyclic seismic loading beyond the frame's yield drift, causing beam lengthening). Beam elongation causes perimeter frame columns, especially corner columns, to pull away from the diaphragm. This creates gaps between the floor diaphragm and perimeter frame, eliminating compression strut load-paths (Fenwick et al., 2010). Additionally, in the case of 80TT, the precast columns had a smooth interface with the floor diaphragm and no starter bars to tie the columns in, which meant the "rubble" mechanism described in the ReCast research (Parr, 2023) would not be available as a load path. Diaphragm struts landing into the ends of perimeter frame beams (especially at corner columns) were considered unreliable for a length proportional to the magnitude of inelastic frame rotation under seismic demands.

The assessment of the existing structure identified the hollow-core flooring units of all levels in the tower were susceptible to one or more brittle failure mechanisms due to their seating connection detailing and the magnitude of assessed drift demands. The brittle failure mechanisms, which can result in the loss of gravity support, as identified include:

- positive moment failure (PMF),
- negative moment failure (NMF),
- loss of seating (LoS), and,
- alpha and beta unit cracking.

For more information on these failure mechanisms and descriptions of different unit types, refer to the SESOC Journal ReCast special bulletin (Brooke et al, 2022).

3 PROJECT BRIEF

The project team's objective for the tower was a retrofit solution to achieve ≥100% NBS in accordance with The Guidelines, as well as incorporating guidance generated out of the ReCast programme. This was an ambitious objective, driven by the Owner's desire to lead the market and demonstrate best practice.

These objectives achieved two outcomes: adaptive re-use for optimal sustainability, and seismic performance aligned with modern expectations, significantly improving building resilience and occupant safety. The project was an early adopter of incorporating guidance from ReCast, and this required adaptation of research guidance into new building-specific acceptance criteria to govern the retrofit design. The ReCast outcomes considered to inform design acceptance criteria, and the subsequent acceptance criteria are as follows:

- Undesirable failure mechanisms for both diaphragms and hollow-core units are primarily driven by drift/rotational demands. The extent of hollow-core retrofit should be targeted on a unit-by-unit basis to avoid unnecessary expense – with retrofits only applied to units subjected to drift demands beyond the threshold required to initiate a brittle failure mechanism (Brooke et al, 2022). Based on this criterion, all units were to be assessed for the full range of brittle failure mechanisms. All units beyond damage thresholds would be retrofitted for their specific identified failure mechanisms, or drift demands would be reduced below the damage thresholds.
- Retrofits can be used to either prevent brittle failure mechanisms or provide a secondary load-path, and ReCast provides design guidance for these retrofits (Brooke et al, 2022). For 80TT, all hollow-core retrofits were to be designed in accordance with ReCast guidance, exceeding the requirements of "The Guidelines".
- Hollow-core units should be assessed for existing damage. Units with existing cracking indicative of brittle failure mechanism initiation should be retrofitted to provide reliable support (Brooke et al, 2022), regardless of the expected performance in relation to drift demand thresholds. For 80TT, all hollow-core units in the building were surveyed for damage and, where applicable, retrofitted in a way that would address the specific observed damage.
- For the reinforced concrete frame subjected to high drift demands that cause inelastic beam rotations and beam elongation:
    - Diaphragm compression struts cannot reliably land directly into columns, and
    - Diaphragm compression struts can land in perimeter and interior beams across wide cracks in the floor perimeter provided ductile reinforcement crosses the crack and the crack width is limited to approximately ¼ of the concrete aggregate size. For typical concrete mixes with 19 mm aggregate (as for 80TT), this maximum crack width is approximately 5 mm. (Parr, 2023).

  Based on this guidance, for 80TT, diaphragm load-paths were not to include struts landing directly into columns and diaphragm ties were to be sized to limit elongation between connections to less than 5 mm to maintain strut load-paths (providing stiffness criteria, typically in excess of strength criteria provided by "The Guidelines").

A key challenge identified early in the project was the high ULS drifts and ductility of the existing structure, typical of 1980s design practice. These high drifts (for the existing unretrofitted structure) meant hollow-core units at all levels of the tower would require local retrofit, and primary structural frames would undergo inelastic rotations, degrading diaphragm load-paths due to secondary effects of beam elongation. Early discussions with the Contractor concluded that retrofitting all hollow-core units in the tower would not be economically feasible.

Further collaborative discussions led to the project team adopting a hybrid retrofit design philosophy. Where reasonably achievable, the tower global structural performance would be improved through the installation of viscous dampers to reduce frame drifts below the threshold requiring hollow-core retrofit. For floor levels remaining above the threshold to trigger brittle hollow-core failure mechanisms following viscous damper installation, local retrofits would be installed. The global structural improvement provided by the viscous dampers had the additional benefits of reducing floor accelerations and reducing the magnitude of frame plastic rotations (and associated beam elongation) under earthquake demands. Frame rotations were reduced in upper portions of the tower to the elastic range, effectively eliminating beam elongation. These reductions assisted by reducing diaphragm design actions and maintaining diaphragm compression load-paths (by preventing or reducing columns pulling away from the building) respectively.

Installation of viscous dampers had significant cost associated (relative to single unit or diaphragm local retrofits). Iteration was required, with regular input from the Contractor, to determine the minimum extent of dampers needed to meaningfully reduce the extent of local retrofit required.

The Contractor also conducted a damage survey of all hollow-core units in the building with support from the Engineer to identify any damaged hollow-core units and record their specific damage. This allowed the Engineer to assess and identify all hollow-core units requiring retrofit at floor levels where the ULS design drift demands were below the threshold requiring standardised hollow-core retrofit.

4 RETROFIT SOLUTIONS

4.1 Supplemental Damping

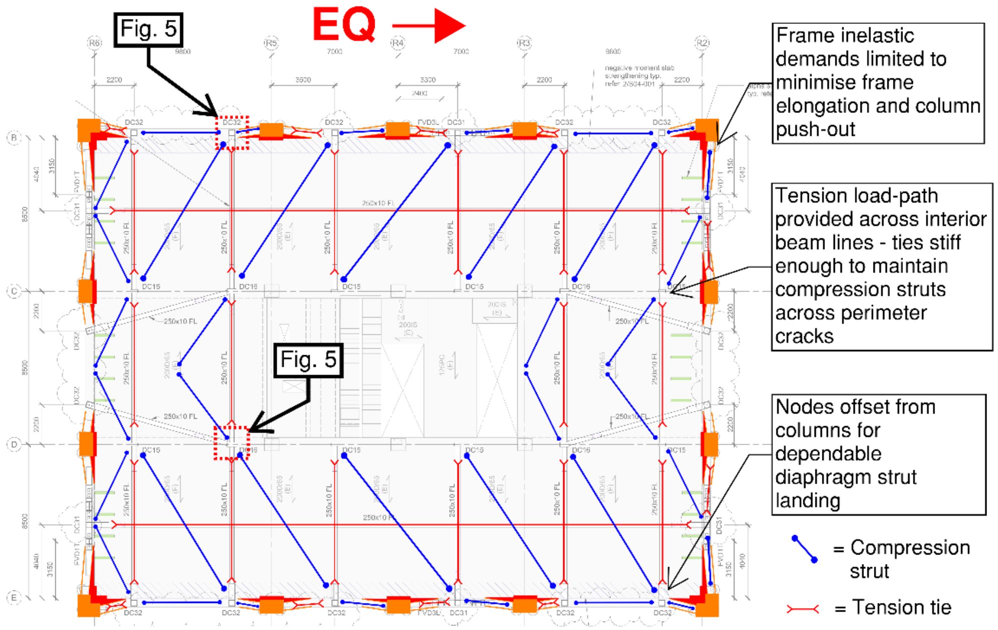
Supplemental dampers were installed at the lower levels of the tower (Figure 2) to improve the seismic frame performance. This retrofit methodology provided reductions to both the drifts and accelerations for the structure, reducing the extent and magnitude of retrofit required for the hollow-core units, the diaphragms and various secondary structural elements. The number of levels retrofitted with supplementary dampers was tuned to minimise the total extent of retrofit required for the structure while achieving the project objectives. For further information on the supplementary damper system, refer to related paper (Pettinga et al, 2024).

4.2 Diaphragm Retrofit

The moment frame is on the exterior face of the building's façade; therefore, constructability considerations were a key factor in developing diaphragm retrofit solutions. To reduce the amount of complex work being completed at height on the exterior of the building the retrofit solution sought to use heavier but fewer connections. To achieve this, floor-mounted steel ties were installed at each tower level to form the ties of a strut-and-tie to complete diaphragm load-paths (with existing floor topping concrete providing strut elements).

Strut-and-tie loading demands were determined by evaluating the structural response to a 1-in-2500-year seismic event using non-linear time history analysis. This return period was selected to represent a Collapse Avoidance Limit State (CALS), as an alternative to using ULS demands multiplied by a building overstrength factor as typically used for modified pseudo equivalent static analysis (pESA). The pESA approach is also considered conservative for taller buildings with low ductility, therefore adopting a CALS allowed a more efficient design (Standards New Zealand, 2004).

The layout selected for the macro strut-and-tie load-path placed nodes within the beams outside of their plastic hinge zones (Figure 4). This arrangement avoided relying on struts transferring load from the floor directly into columns, which would have required substantial local remediation to instate dependable load-paths. The connection locations within the beams, when coupled with reduction of global frame inelastic rotations, provided dependable strut landing locations into the perimeter frames, incorporating ReCast guidance.



Frame inelastic demands limited to minimise frame elongation and column push-out

Tension load-path provided across interior beam lines - ties stiff enough to maintain compression struts across perimeter cracks

Nodes offset from columns for dependable diaphragm strut landing

= Compression strut

= Tension tie

Figure 4: Diaphragm macro strut-and-tie retrofit layout and example load-path

A kit of parts approach was used for the diaphragm steel ties and connections. Different connection concepts were iterated and refined with Contractor input, until three typical details were settled on that could be scaled up and down in capacity as required (rather than using 30-to-40 bespoke connections). This approach minimised the complexity of the shop drawing process, allowed for a standardised system of hole location tolerances for avoiding existing reinforcement, and allowed for standardised waterproofing details for perimeter connections penetrating outside of the building cladding line. Refer Figure 5 for images of typical exterior and interior connection details (shown prior to completion of grouting and waterproofing).

The steel tie typical sections were sized to satisfy stiffness criteria, limiting total tie elongation to less than 5 mm (based on ReCast guidance) to prevent diaphragm perimeter edge cracks opening wide enough to compromise the struts. Necked sections were used in each tie which were sized to ensure the tension load in the tie matched the tension demand determined by the analysis and protect connections from unintended overloading. Rectangular sections were used with a standard 10 mm depth to allow for rebating into the floor topping.

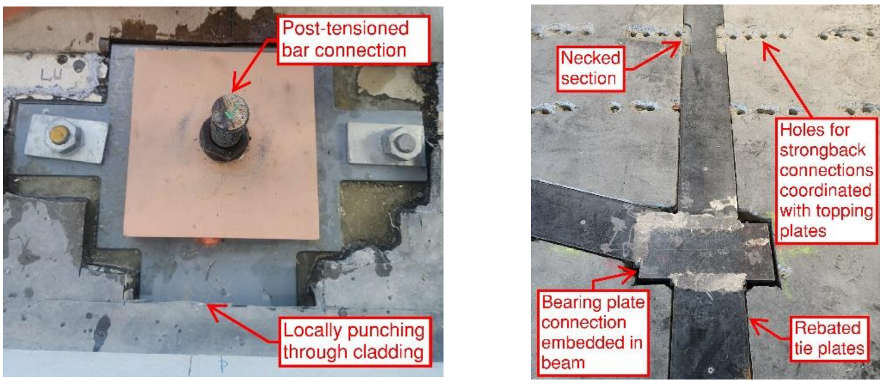


Figure 5: Partially installed diaphragm tie plates and connections – exterior perimeter beam connection (left), interior beam connection (right)

Column ties were also provided between perimeter frame columns and interior frame columns on approximately every third floor. These were installed only to provide restraint to the exterior columns to maintain column axial compression capacity, and not as part of the diaphragm load-path.

4.3 Hollow-core Retrofit

Four retrofit details were installed to remediate hollow-core units.

For typical interior units susceptible to PMF or LoS, strongback retrofits were installed. The design of strongbacks was informed by ReCast guidance (Büker et al, 2022). Due to the large number of strongbacks required on the project, the collaboration between the Engineer and Contractor allowed the refinement of detailing to minimise fabrication costs.

An initial exercise was undertaken to determine the most effective fixing type for fixing the strongbacks to hollow-core units above for the project constraints. As noted in the ReCast papers, the use of screw anchors provides the benefit of allowing installation from the floor below only, minimising disruption by the retrofit construction to one floor instead of two. However, for 80TT the building was untenanted during construction works, making this less critical. Trial installations of design options showed that through-bolted connections were more cost-effective than screw anchors. This was because through-bolts allowed for fewer fixings, greater installation tolerances, and lower material supply costs

Significant fabrication cost savings from standard strongback detailing were achieved by designing with thicker plates to eliminate the need for stiffeners and minimising structural welds by identifying compression-only connections (Figure 6).

For typical interior units susceptible to NMF, new reinforcing bars were installed using an epoxy-filled chase in the floor topping (Figure 7) to increase the units' negative moment capacity envelope and prevent initiation of critical negative moment cracks.

The Contractor identified a critical challenge; lapping the new bars with existing starter bars that connect into the exterior beams. The "typical" ReCast detail would require substantial demolition and reinstatement of the existing facade. To address this, the team developed an alternative detail to achieve the same design intent as the ReCast detail, using extension bars welded to existing starters and epoxied into chases cut in to the floors. This required non-destructive scanning to locate the existing floor starter reinforcement and expose it while avoiding damage. This approach worked well, avoiding the façade, and also improving safety on site, as no works were required outside the facade (at height) to install these retrofits.

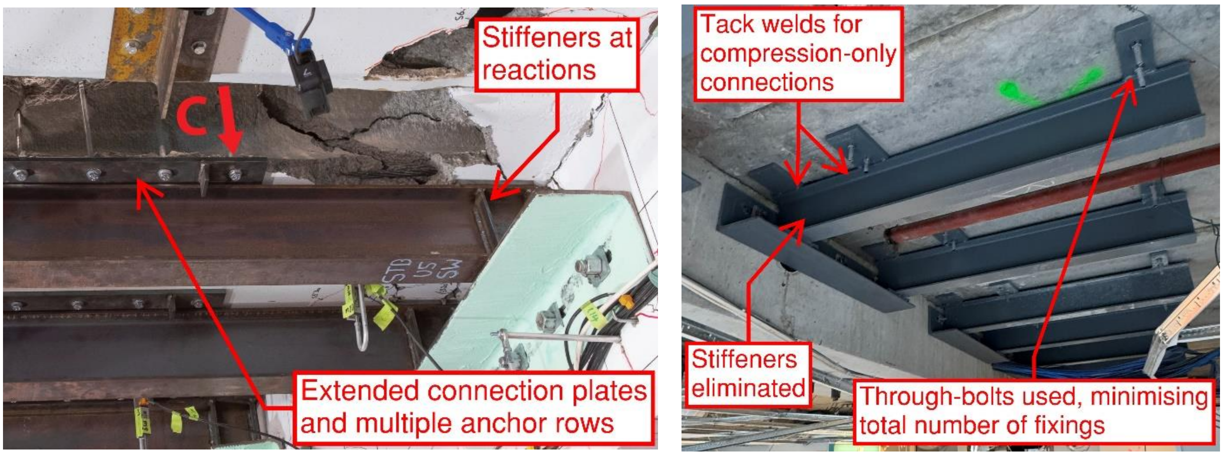
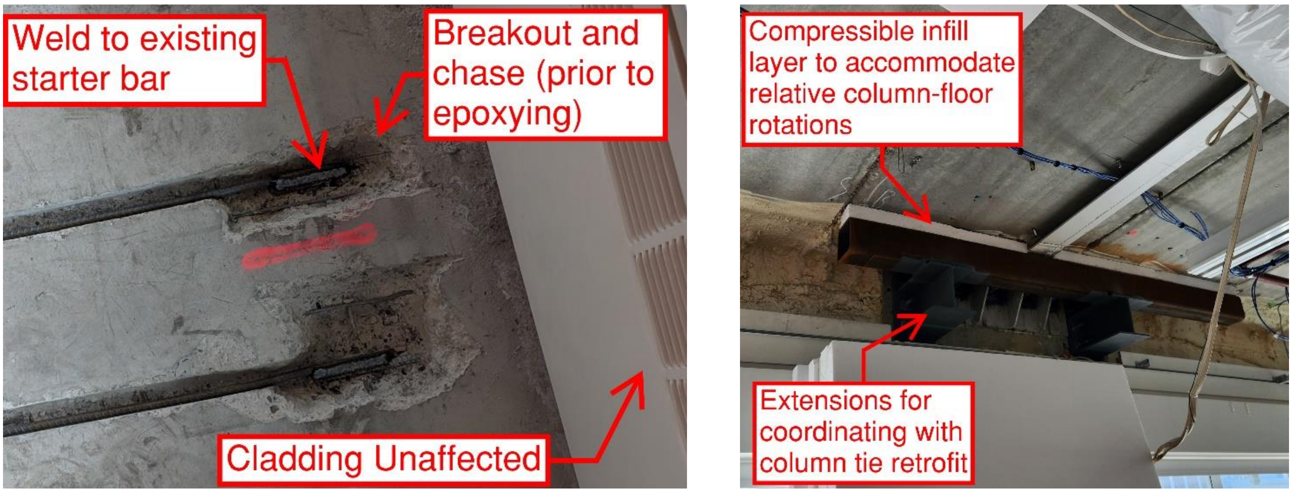


Figure 6: ReCast strongback detailing (left) (Büker et al, 2022), 80TT strongback detailing (right)



(a) view looking at floor topping with chased in bars

(b) view of underside of hollow-core unit and column – showing the catch frames

Figure 7: Welded NMF retrofit to avoid cladding demolition (a), adapted beta unit catch bracket (b)

For beta units susceptible to web-cracking and shear failure, beta unit catch frames were installed (Figure 7). These applied the design principles provided by ReCast for the support interface (Parr, 2023) but used additional extensions to allow for interfacing with column tie retrofits and a range of different support column conditions. When extending the support location, careful consideration was given to resolving additional eccentricities and accommodating three-dimensional relative rotation between the supporting column and the supported beta units.

For alpha units, a mixture of alpha unit corner catch frames and strongbacks were used for end supports (Figure 8). For the interior spans of alpha units, plate hanger retrofits designed in accordance with ReCast recommendations (Parr, 2023) were installed to prevent the bottom flange from separating in the event web-splitting cracks propagated the full unit length.

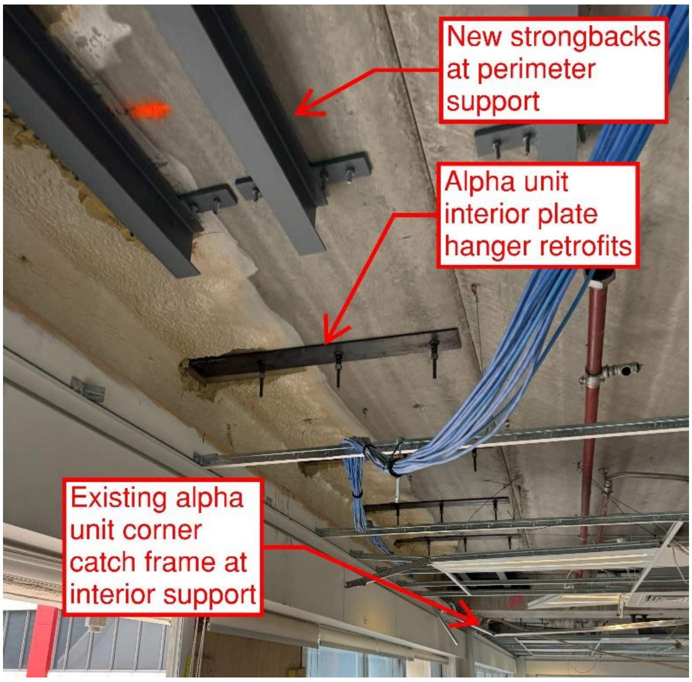


Figure 8: Alpha unit retrofits

5 CONCLUSION

Retrofit of existing reinforced concrete buildings with hollow-core floors in high seismic zones (like Wellington) is often seen as prohibitively costly.

The key factors on this project that have helped negate this are:

- Active early contractor involvement to optimise construction methodology.
- Targeted performance improvement of the global structural system.
- Careful consideration of detailing.
- Sustained effort and commitment from all parties.

With a holistic and collaborative approach, adaptive reuse of a building can be a competitive and sustainable solution for building owners – even when targeting high performance goals and incorporating latest research outcomes.

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