RECAST FLOORS PROJECT: OVERVIEW AND KEY RECOMMENDATIONS

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1 INTRODUCTION

Precast concrete floors comprise precast floor units with in-situ (often lightly) reinforced concrete topping to form a composite floor system that generally also functions as a diaphragm. Such floors are a common feature of New Zealand buildings, being almost ubiquitous during the 1980s and early 1990s.

Four types of precast floor units are commonly encountered in New Zealand, namely

- hollow-core
- double tee
- ribs (with timber infill), and
- flat slabs.

All of these precast floor units are typically prestressed. Precast floors constructed using hollow-core and double tee units are distinguished by typically having longer spans and/or supporting heavier loads than rib or flat slab floors. Historically, a grey area existed regarding how responsibility for the design of precast concrete floors and their supports was divided between precast suppliers and the structural engineer for a building (Hare et al. 2009). Perhaps consequently, precast concrete floors were previously designed and constructed in ways that make the floors prone to poor performance during earthquakes, as has been documented previously (Corney et al. 2014; Fenwick et al. 2010; Hare et al. 2009; Henry et al. 2017; MBIE et al. 2018). Support conditions for units in existing buildings are likely to lead to significant damage and potentially collapse during design-level earthquakes.

Buildings with precast floors comprise a large percentage of the commercial building stock in all New Zealand cities. The Department of Building and Housing (now part of MBIE) found in 2007 that between Auckland, Wellington, and Christchurch, some 1.5 million square metres of hollow-core floor planks alone were supplied between 1981 and 2003 (DBH 2007). Anecdotal evidence based on post-earthquake inspections of buildings suggests that over 60% of commercial floor area in Wellington falls in this category. Observations suggest the proportion in Christchurch would have been similar until the earthquakes of 2010 and 2011, and there is no reason to think the situation is any different in Auckland and other major centres. While originally installed predominantly in commercial buildings, there are increasingly more residential buildings with older precast floor details as more buildings are being converted from commercial to residential use in major centres.

New Zealand's extensive use of precast floors in regions of high seismicity is unusual, with in-situ floors more commonly used internationally. Consequently, and in contrast to most other deficiencies found in existing buildings, little international research is available regarding the adequacy of existing precast floors. In this sense, the seismic performance of precast floors is "New Zealand's problem".

The collapse of double tee units in Statistics House (MBIE 2017, 2018) and widespread damage to other precast floors during the earthquakes that affected Christchurch and Wellington in recent years (Corney et al. 2014; Henry et al. 2017) has highlighted the risk that failure of precast floors can pose to building occupants. These events have also focussed attention on the difficulties of assessing and improving existing precast floors. The assessment of existing precast concrete floors is covered by Section C5 of the New Zealand seismic assessment guidelines (MBIE et al. 2017). The precast floor provisions saw a significant update in 2018 (MBIE et al. 2018) based in part on knowledge gained from the performance of precast floors in the Kaikoura Earthquake. The development of the update (MBIE et al. 2018) identified that significant unanswered questions existed regarding the performance and retrofit of precast concrete floors. The fact that no retrofit solutions for deficient precast concrete floors had been fully validated experimentally was a particular concern.

Recognising the urgent industry need for answers to these questions, funding was obtained from BRANZ in 2018 for an extensive three-year multi-agency research programme to address remaining questions about the performance and improvement of existing precast floors. The research programme, which has been dubbed the ReCast Floors (Retrofit of preCAST FLOORS) project, received further funding from EQC, QuakeCoRE, and Concrete NZ.

PAPER CLASS & TYPE: RESEARCH REFEREED

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The ReCast Floors project has two primary aims, namely:

- Improving understanding of the likely behaviour of precast floors during earthquakes, including the performance of earthquake-damaged precast concrete floors, and
- Developing and validating methods for improving the performance of existing precast concrete floors.

As outlined in this paper and summarised in Figure 1, ReCast Floors has investigated these topics in several different ways, including numerical simulations, full-scale laboratory tests, and 'real-world' investigations. These investigations have been undertaken by researchers from University of Auckland, University of Canterbury, and BRANZ, in close collaboration with structural engineering practitioners. The ReCast Floors project has supported four PhD students, one Masters student and several research assistants.

An industry advisory committee was assembled to ensure the focus and direction of the programme remained relevant to the needs of practicing structural engineers. This panel comprises representatives of stakeholder groups including SESOC, NZSEE, Concrete New Zealand Precast and Learned Society, Wellington City Council, and UC Quake Centre. The advisory group provided input on the direction of the research throughout the research programme, including during the development of potential retrofit solutions.

The ultimate goal of the ReCast Floors project was to assemble design guidance for the assessment and improvement of precast concrete floors. This special issue of the SESOC Journal achieves this goal by providing a summary of all aspects of ReCast Floors project to date, with a specific focus on recommendations of interest to structural engineers assessing and retrofitting building with precast floors. The purpose of this first paper is to provide an overview of the research programme and a summary of the key recommendations found in the rest of the special issue.

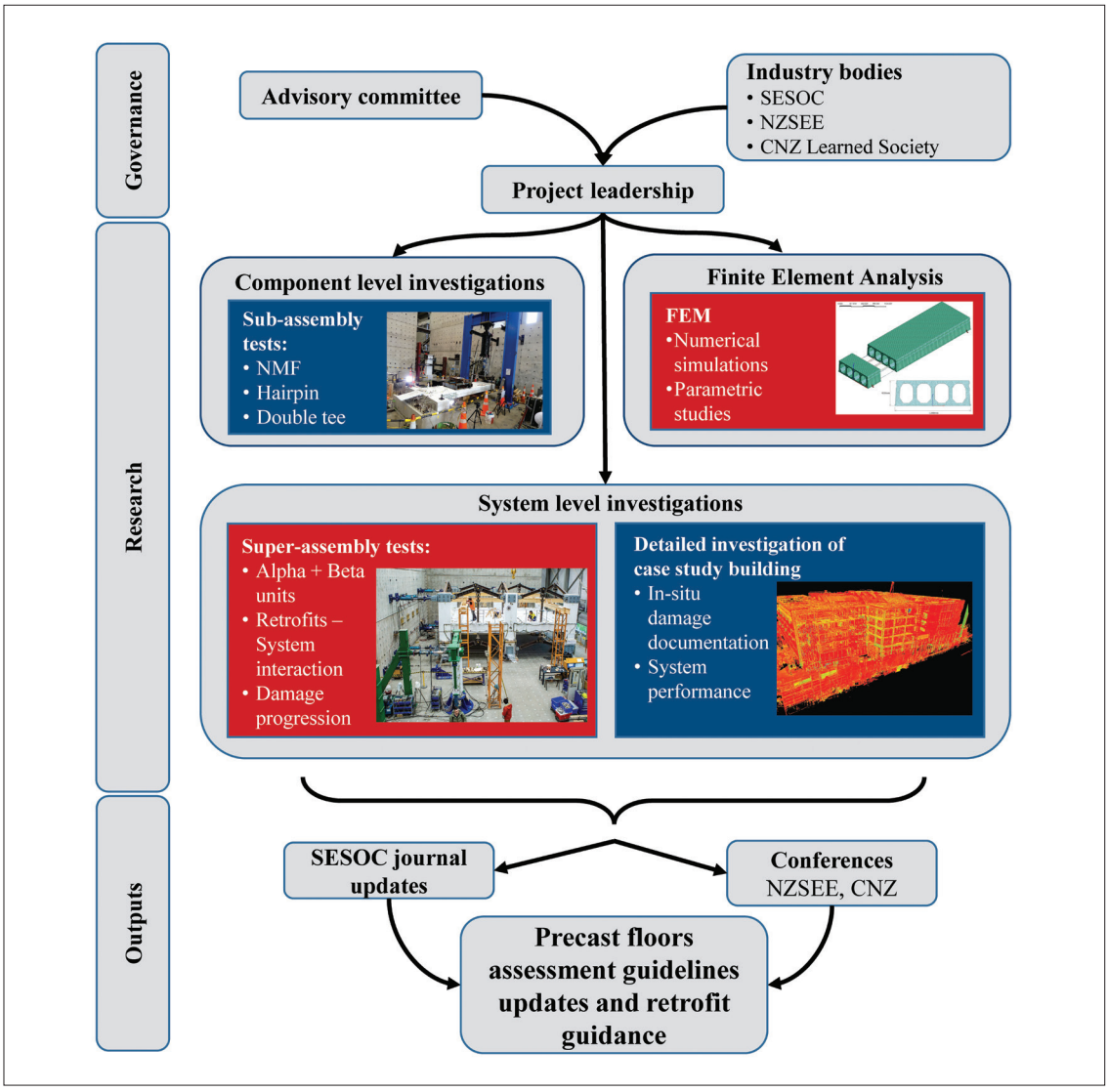

Figure 1: Overview of research projects, oversight arrangements, and outputs

2 SUMMARY OF RESEARCH PROGRAMME

As shown in Figure 1, research under the ReCast Floors project included:

- Finite element analysis of failures in hollow-core units.
- Component-level investigations using single-unit tests (Figure 2) to explore:
  - retrofits for negative moment failure of hollow-core,
  - performance of hollow-core with hairpin reinforcement, and
  - retrofits for flange-hung double-tee.
- System-level investigations via super-assembly tests (Figure 3) and detailed investigation of a damaged case study building to explore the interaction of the supporting frame and hollow-core units under three-dimensional demands.

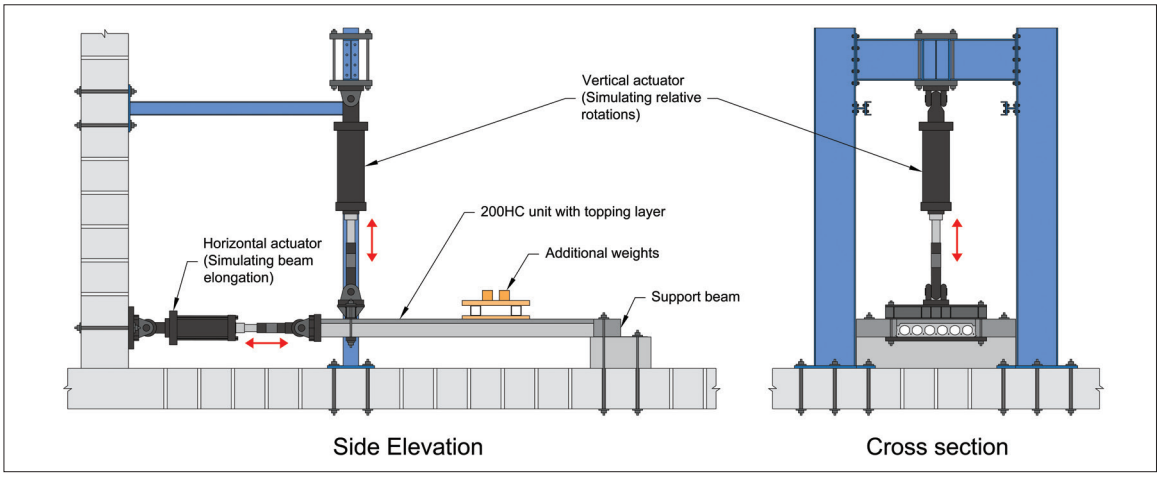

Figure 2: Example sub-assembly test arrangement

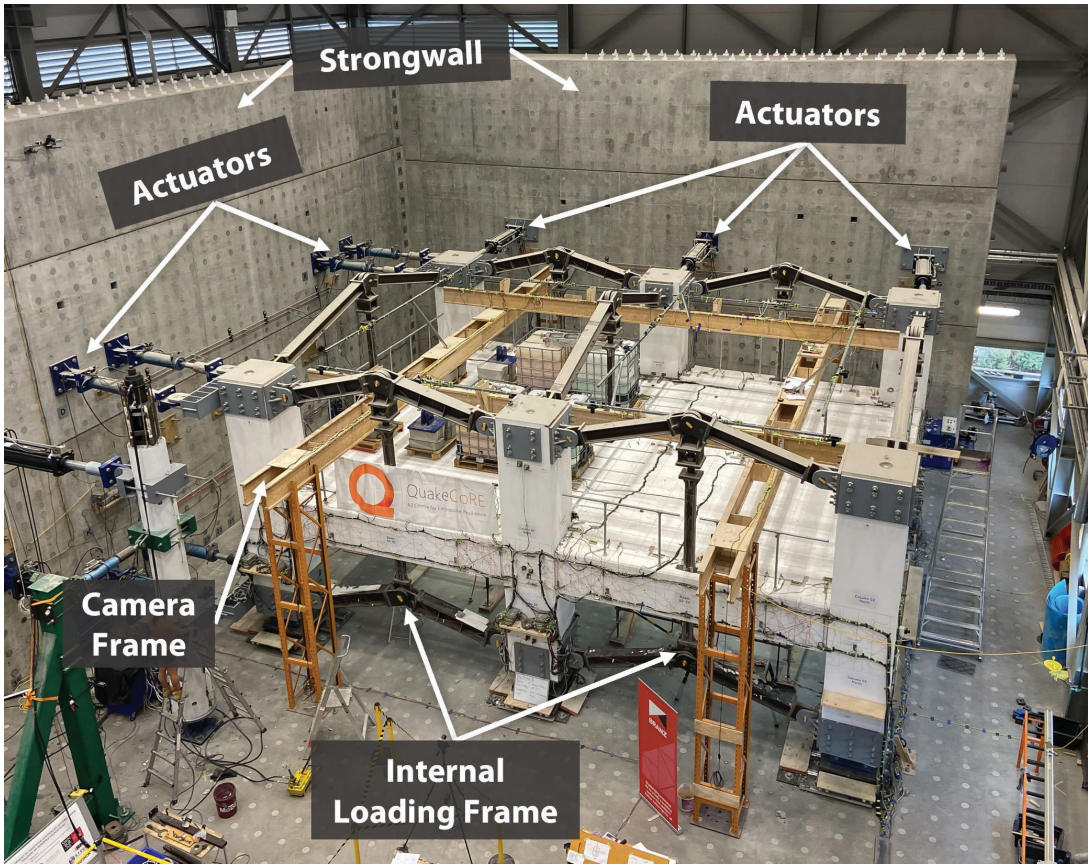

Figure 3: Super-assembly specimen (Büker et al 2022)

The experimental programme was very extensive including a total of 8 hollow-core shear tests, 10 hollow-core sub-assembly tests, 6 precast-tee single unit tests, and 2 super-assembly tests.

Furthermore, a very detailed damage survey of a building with hollow-core floors damaged during the Kaikoura earthquake was undertaken. The survey included 873 laser scans and over 105,000 photos, some of which were stitched together into three-dimensional renderings of the building, enabling a virtual post-earthquake inspection.

3 SESOC SPECIAL ISSUE

This issue of the SESOC Journal provides a summary of key outputs of the ReCast Floors project, with a specific focus on key observations and recommendations of interest to engineers engaged in seismic assessment and retrofit of buildings with precast floors. The intent is that this issue serves as a reference tool for engineers when facing challenges with assessment and retrofit of precast floors on future projects.Table 1 provides a list of all papers in the special issue. Papers have been organised by the following overarching themes: retrofits, building investigations, assessment and damage of hollow-core floors, diaphragm performance, and finite-element analysis.

Note that a further paper from the ReCast Floors project on the performance of double-tee floor systems and testing of retrofit solutions is expected to be published in the near future.

Table 1: Special issue papers

Topic	Paper No	Authors	Title	Page
Retrofits	1	Brooke, Büker, Bull, Elwood, Henry, Hogan	Overview of retrofit requirements and techniques for precast concrete floors	30
	2	Büker, Hogan, Brooke, Elwood, Bull	Design recommendations for seating angle retrofits	55
	3	Büker, Brooke, Hogan, Elwood, Bull, Sullivan	Design recommendations for strongback retrofits	69
Building investigations	4	Mostafa, Hogan, Elwood	Seismic performance of precast hollow-core floors with modern detailing – A case study	86
	5	Liu, Henry, Hogan, Brooke	Real world experience of seismic performance and retrofits used in buildings with hollow-core floors	102
Assessment and Damage of hollow-core floors	6	Mostafa, Hogan, Elwood	Torsional capacity assessment of precast hollow-core floors	109
	7	Büker, Parr, De Francesco, Hogan, Bull, Elwood, Liu, Sullivan	Seismic damage observations of precast hollow-core floors from two full-scale super-assembly tests	125
Diaphragm performance	8	Parr, Büker, De Francesco, Bull, Brooke, Elwood, Hogan, Liu, Sullivan	Load-path and stiffness degradation of floor diaphragms in reinforced concrete buildings subjected to lateral loading - Part I, Experimental observations	149
	9	Parr, Bull, Brooke, De Francesco, Elwood, Hogan, Liu, Sullivan	Load-path and stiffness degradation of floor diaphragms in reinforced concrete buildings subjected to lateral loading – Part II, Data analysis	172
Finite element analysis	10	Sarkis, Sullivan, Brunesi, Nascimbene	Strategies for finite element modelling of precast pre-stressed hollow-core floors	204

4 KEY RECOMMENDATIONS AND OBSERVATIONS

The following provides a quick overview of some of the key outcomes of the ReCast Floors project of value to the structural engineering community. These reference the paper number from Table 1 to facilitate quick reference to the appropriate paper within this special issue for more details. Recommendations are separated below between those that are applicable to all precast floors, those that apply specifically to hollow-core floors, and those applicable specifically to double tee floors.

4.1 GENERALLY APPLICABLE RECOMMENDATIONS

- Precast floor units in certain locations are more prone to damage during earthquakes. This includes "alpha units" that are immediately adjacent to a parallel beam, wall, or other structural element, and "beta units" that are supported at or adjacent to an intermediate column or a wall. The susceptibility of (particularly hollow-core) beta units to damage is not addressed in current assessment guidance (Papers 1, 4 and 7).
- It is typically not possible to retrofit precast concrete floors to achieve more than life safety performance during strong earthquake shaking. During such shaking, retrofitted floors are expected to sustain damage that may be difficult or impossible to repair (Paper 1).
- It is critical that deformation (in)compatibility between precast floor units, retrofit components and primary structure be considered when designing and detailing retrofits for precast floors (Paper 1).
- Strong preference should be given to retrofits that have been shown experimentally to be able to accommodate the interaction of deformations in three dimensions that affect the behaviour of precast floors (Paper 1).
- Load combination used for design of retrofits of precast floors should be different from that used for retrofits of the lateral system, reflecting the role of precast floors to provide gravity load support before, during, and after the earthquake (Paper 1).
- Retrofits should be designed and detailed so that they are not prone to brittle failure if overloaded (Papers 1, 2, 3).

Diaphragms were not a primary focus of the ReCast Floors project; however, the super-assembly tests offered a rare opportunity for experimental investigation of diaphragm behaviour. This produced a number of observations and recommendations (Papers 8 and 9):

- A previously unrecognised "rubble interlock" phenomenon allows compression forces to be transferred across wide cracks. However, the rubble interlock mechanism does not result in direct transfer of compression forces to columns as is often assumed in idealised strut-and-tie models of diaphragms.
- The behaviour of diaphragms can be greatly affected by the robustness of topping reinforcement crossing between adjacent beta units.
- Diaphragm load paths may be impacted by degradation of the torsional stiffness of beams at the diaphragm perimeter.
- Diaphragm stiffness degrades substantially as imposed diaphragm deformations are increased. Testing reported in Paper 9 indicates that the diaphragm stiffness can degrade by as much as 75% after drift demands exceed approximately 1%.

Further work is required to determine how these observations should be reflected in diaphragm assessment procedures.

4.2 HOLLOW-CORE FLOORS

Damage observations:

- While the seating details from NZS 3101:2006 Amendment 2 in the case study building addressed loss of seating, positive moment failure, and negative moment failure, they did not prevent severe damage to several beta units, including web cracking. The observed damage patterns are not directly accounted for in the assessment procedures of the Assessment Guidelines. Based on these observations, MBIE is currently initiating public consultation on changes to B1/VM1 such that the seating detail in Figure C18.4 NZS 3101:2006-A3 will not be considered a deemed-to-comply solution. (Paper 4).
- In full-scale super-assembly test, web-cracking was observed at 0.5% inter-storey drift but can be very difficult to detect after earthquake loading (Paper 7).
- Cracks emanating from a soffit crack can propagate at different angles through the webs, including at shallower angles than observed in previous experiments. (Paper 7).
- A gravity test of a web-cracked hollow-core unit demonstrated that such cracking reduces the gravity load capacity of hollow-core floors. Additional research is required to reliably quantify the reduction in the shear capacity (Paper 7).
- Transverse soffit cracks can form away from the support and beyond the typical seating retrofit, but the criticality of this crack depends on the

orientation of the crack and the concrete-to-strand bond on either side of the soffit crack. There is currently no known means of determining if the bond to the strand has been compromised (Paper 7).

Assessments:

- Tools have been provided to simplify torsion assessment of hollow-core units. It is recommended to only consider the equivalent tube section case for assessing the torsional capacity of hollow-core floor units and not consider the flange-only case. (Paper 6).
- Further research is required to improve the current torsional capacity assessment methodology. Limitations of the existing approach suggest that a cautious approach should be adopted when considering whether a retrofit to address torsion is required (Paper 6).
- The assessment guidelines C5 (MBIE et al. 2018) have been found to provide a good indication for the drift capacity of the tested hollow-core floors in full-scale super-assembly tests. However, in many instances, the observed damage patterns did not reflect the predicted governing failure modes (Paper 7).

Retrofits:

The recommendations below are discussed in Paper 1, and in more detail in other papers where noted:

- Retrofits that have been shown experimentally to address one or more failure modes comprise supplementary seating (Papers 2 and 7), strongback supports (Paper 3), the cable catch system, supplementary negative moment reinforcement, catch beams, and cutting of starter bar reinforcement.
- The shallow angle of some positive moment cracks noted in Paper 7 means that supplemental seating alone is not recommended to address positive moment failures (Paper 2).
- Supplementary transverse reinforcement is expected to be an effective retrofit technique, but has not yet been experimentally validated.
- Supplementary positive moment reinforcement has not been demonstrated to be an effective retrofit. It may be useful in conjunction with other measures, but this has not been experimentally validated.
- Infilling of cores and inducement of cracking at the ends of units are not effective retrofit techniques.

4.3 DOUBLE TEE FLOORS

- Double tee floors may be effectively retrofitted using supplementary corbels or articulating hangers. Post-installed Cazaly hangers may also be an effective retrofit, but this has not been demonstrated experimentally (Paper 1).

4.4 FLAT SLAB AND RIB AND INFILL FLOORS

- Retrofit techniques for flat slab and rib and infill floors would be broadly similar to those for hollow-core and double tee floors, respectively (Paper 1).

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6 OTHER RECAST FLOORS REFERENCES

In addition to this SESOC Special Issue, the ReCast Floors project team and collaborators have published results of the research programme and associated activities in various journals and conferences. Below is a chronological list of additional papers either published, submitted, or in development, which may be of further interest to the readers of this special issue.

Corney, S. R., Elwood, K. J., Henry, R. S. Henry. 2018. “Residual capacity testing of damaged hollow-core precast concrete floors.” Proceedings of the 2018 NZSEE Annual Technical Conference, 9. Auckland, New Zealand: New Zealand Society for Earthquake Engineering.

Corney, S. R., Elwood, K. J., Henry, R. S., Nims, D. K. 2018. Assessment of existing concrete buildings in Wellington with precast floors. Kaikoura Earthquake Research Programme (2017-18). Lower Hutt, New Zealand: Natural Hazards Research Platform.

Hare, J., Elwood, K. J., Bull, D. K., Henry, R. S., and Brooke, N. J. 2019. “Precast Double Tee Support Systems - 10 Years On.” SESOC Journal, 32(1), pp.32–40.

Puranam, A., Bueker F., and Elwood, K. J. 2019. “Assessment of reinforced concrete buildings with hollow-core floors.” Proceedings of the 2019 Pacific Conference on Earthquake Engineering, 10. Auckland, New Zealand: New Zealand Society for Earthquake Engineering.

Parr, M., Elwood, K. J., Bull, D. K., Büker F., Hogan L. S., Puranam, A. Y., Henry R. S., and Brooke N. J. 2019. “Development and Testing of Retrofit Solutions for Hollow-core Floors in Existing Buildings.” Proceedings of the 2019 Concrete New Zealand Conference, 12. Dunedin, New Zealand: Concrete New Zealand

Büker, F., Poland C., and Brooke N. J. 2020. “Assessment of Existing Precast Concrete Floors: Hollow-core Worked Example - Revision 1.” Journal of the Structural Engineering Society New Zealand, 33 (2): 44–86.

De Francesco, G., and Sullivan,T. J. 2021. “Experimental loading protocols to evaluate the seismic performance of floor systems.” Proceedings of the 2021 NZSEE Annual Technical Conference, 12. Christchurch, New Zealand: New Zealand Society for Earthquake Engineering.

Sarkis, A. I., and Sullivan,T. J. 2021. “Finite element analyses of hollow-core units subjected to shear and torsion.” Proceedings of the 2021 NZSEE Annual Technical Conference, 8. Christchurch, New Zealand: New Zealand Society for Earthquake Engineering.

Büker, F., Brooke, N. J.,Elwood, K. J., Bull, D. K., Hogan, L. S. and Parr, M. 2021. “Development and Validation of Retrofit Techniques for Hollow-core Floors.” Proceedings of the 2021 SESOC Conference, 14. Hamilton, New Zealand: Structural Engineering Society New Zealand.

Corney, S. R., Puranam, A. Y., Elwood, K. J. Henry, R. S. and Bull, D. K. 2021. “Seismic Performance of Precast Hollow-Core Floors: Part 1—Experimental Data.” ACI Structural Journal, 118 (5): 49–64. https://doi.org/10.14359/51732821.

Puranam, A. Y., Corney, S. R., Elwood, K. J., Henry, R. S. and Bull, D. K. 2021. “Seismic performance of precast hollow-core floors: Part 2-assessment of existing buildings.” ACI Structural Journal, 118 (5): 65–77. https://doi.org/10.14359/51732822.

Mostafa, M. T., Büker, F., Hogan, L. S., Elwood, K. J., Bull, D. K. and Parr, M. 2022. “Seismic Performance of Precast Hollow-core Units Seated Within the Plastic Hinge Region (accepted).” Proceedings of the 2022 NZSEE Annual Technical Conference, 12. Wellington, New Zealand: New Zealand Society for Earthquake Engineering.

De Francesco, G., Sullivan, T. J., and Nievas, C. I. (Accepted). “Highlighting the need for multiple loading protocols in bi-directional testing.” Bulletin of the New Zealand Society for Earthquake Engineering, 15.

Sarkis Fernandez, A., Bueker F., Sullivan, T., Elwood, K. J., Brunesi, E., and Hogan, L. S. (Accepted). “Aspects affecting the nonlinear behavior of precast pre-stressed hollow-core units failing in shear.” Structural Concrete. https://doi.org/10.1002/suco.202100579.

Henry, R. S., and Jenkins, M. (In Development). “Retrofit Techniques for Double-Tee Floors: Experimental Investigation and Design Recommendations.” SESOC Journal.

Mostafa, M., Hogan, L. S., Stephens, M., Olsen, M. J., & Elwood, K. J. (In Development). “A Detailed Damage Investigation of an Instrumented Building Damaged During the M-7.8 Kaikoura Earthquake”. Earthquake Spectra.

7 REFERENCES

Corney, S. R., Henry, R. S., and Ingham, J. M. 2014. “Performance of Precast Concrete Floor Systems During the 2010/2011 Canterbury Earthquake Series.” Mag. Concr. Res., 66 (11): 563–575.

DBH. 2007. Hollowcore Floor Overview Report. 23. Wellington, New Zealand: Department of Building and Housing.

Fenwick, R. C., Bull, D. K., and Gardiner, D. R. 2010. Assessment of Hollow-Core Floors for Seismic Performance. 152. Christchurch, New Zealand: Department of Civil and Natural Resources Engineering, The University of Canterbury.

Hare, J., Fenwick, R. C., Bull, D. and Built, R. 2009. “Precast Double Tee Support Systems.” J. Struct. Eng. Soc. N. Z., 22 (1): 10–44.

Henry, R. S., Dizhur, D., Elwood, K. J., Hare, J. and Brunsdon, D. 2017. “Damage to Concrete Buildings with Precast Floors During the 2016 Kaikoura Earthquake.” Bull. N. Z. Soc. Earthq. Eng., 50 (2): 174–186.

MBIE. 2017. Investigation into the Performance of Statistics House in the 14 November 2016 Kaikoura Earthquake. 36. Wellington, New Zealand: Ministry of Business, Innovation, and Employment.

MBIE. 2018. Addendum: Investigation into the Performance of Statistics House in the 14 November 2016 Kaikoura Earthquake. 25. Wellington, New Zealand: Ministry of Business, Innovation, and Employment.

MBIE, NZSEE, EQC, NZGS, and SESOC. 2017. The Seismic Assessment of Existing Buildings: Technical Guidelines for Engineering Assessments. Technical Guidelines for Engineering Assessments. Wellington, New Zealand: Ministry of Business, Innovation, and Employment.

MBIE, NZSEE, EQC, NZGS, and SESOC. 2018. Technical Proposal to Revise the Engineering Assessment Guidelines - Part C5 Concrete Buildings. 252. Wellington, New Zealand: Ministry of Business, Innovation, and Employment.

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