Bulletin of the New Zealand Society for Earthquake Engineering, Vol. 55, No. 1, March 2022

OPINION PAPER

INDUSTRY IMPACT OF QUAKECORE FLAGSHIP PROGRAMME 4

Matthew J. Fox[1] and Jared M. Keen[2]

(Submitted *August 2021*; Reviewed *September 2021*; Accepted *October 2021*)

ABSTRACT

QuakeCoRE is one of 10 Centres of Research Excellence funded by the New Zealand Tertiary Education Commission. With a focus on earthquake resilience of communities and societies, it has played a major role in addressing needs identified following the Christchurch Earthquake and other major events over the last decade. QuakeCoRE comprises a number of Flagship Programmes, including Flagship 4, which is entitled "Next-generation infrastructure: Low-damage and repairable solutions." This paper aims to support turning research into practice by identifying the key areas of Flagship 4 that are likely to have an impact on the industry. Five key areas of impact were identified, based on a review of the published research, engagement with Flagship 4 leadership and the authors' experience in the industry. For each area identified, summaries of the major research outcomes are provided, along with views as to how these can support the engineering practice.

INTRODUCTION

This opinion piece aims to provide practicing engineers with a summary of the research findings relating to Flagship 4 of QuakeCoRE, particularly those aspects that the authors consider to be most impactful on industry. The research of QuakeCoRE and Flagship 4 is considered to represent much of the most important seismic and structural engineering research in New Zealand in the past decade.

For academic research in earthquake engineering to have a tangible impact, it is important that key findings and recommendations are widely disseminated to industry. An overview of QuakeCoRE and Flagship 4 is provided, followed by five sections on the areas that, in the authors' opinion, are likely to have the most significant impact on the industry. Each section highlights key research activities and findings, and comments on why they are likely to be impactful. Concluding remarks are then provided, with a focus on how practising engineers can make the most of the QuakeCoRE Flagship 4 research.

OVERVIEW OF QUAKECORE AND FLAGSHIP 4

QuakeCoRE formed in 2016 and is one of 10 Centres of Research Excellence (CoREs) currently funded by the Tertiary Education Commission. With funding of ~NZ$4 million per annum through to 2021, and recent additional funding through to 2028, QuakeCoRE focuses on earthquake resilience of communities and societies through innovative world-class research, human capability development, and deep national and international collaborations. QuakeCoRE is hosted by the University of Canterbury and has seven other formal research partners.

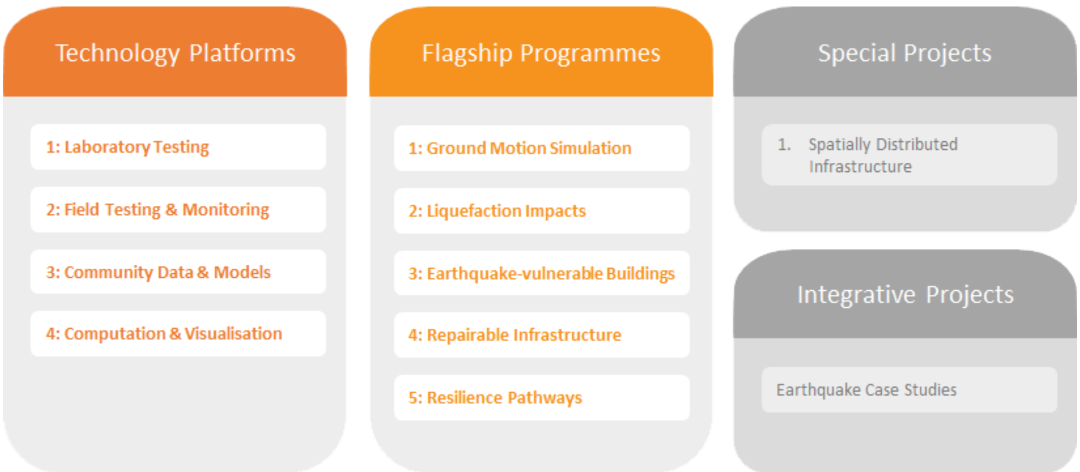

Figure 1: QuakeCoRE research organisation structure for period 2016-2021 (www.quakecore.nz/research).

[1] *Corresponding Author, Researcher, University of Pavia, Italy, mat.j.fox@gmail.com (Member)*
[2] *Technical Director, Beca Ltd, Christchurch, jared.keen@beca.com (Member)*

The 2016-2021 research programme was organised into Technology Platforms, Flagship Programmes, Integrative Projects, and Special Projects, as outlined in Figure 1. The Flagship Programme 4 was entitled "Next-generation infrastructure: Low-damage and repairable solutions" and it aimed to achieve a new design paradigm whereby reparability and damage-control is explicitly considered in the design process. Flagship 4 thus provided much of the research underpinning the structural response to the Canterbury and Kaikōura earthquakes. Within Flagship 4 there were three key thrust areas, each with specific deliverables, as outlined in Table 1.

Table 1: Flagship Programme 4 key thrust areas and associated deliverables.

Key thrust areas		Deliverables
1: New technologies for buildings	1.1	Develop low-damage systems for buildings, including guidance for their design and construction
	1.2	Development of a risk-targeted design methodology for new systems
2: Performance objectives and	2.1	Develop methodology for assessing residual capacity of building structures
	2.2	Use of large-scale test results for validation of models to assess performance
	2.3	Develop improved means of considering reparability within the performance assessment of new and conventional systems
	2.4	Develop alternative repair strategies for existing structures considering advanced performance measures
3: Implementation	3.2	Identify means to implementation of low-damage systems
	3.3	Propose alternative methods to assess performance of traditional building solutions with that of low-damage systems

Industry engagement is an important aspect of QuakeCoRE and Flagship 4. Dissemination of research outcomes to the industry allows engineers, regulators, and other stakeholders to incorporate findings into practice, which helps achieve the societal benefits that QuakeCoRE targets. Furthermore, industry engagement allows the needs of the industry to be communicated back to the academic community to help guide their research direction.

The authors have investigated the research undertaken as part of Flagship Programme 4 to form a view on the aspects most likely to have an impact on the industry. This view is formed based on industry perspective, review of research outputs, and engagement with Flagship Programme 4 leadership through Industry Representative and Industry Affiliate roles.

The authors' view is that there are five key areas of Flagship 4 research, closely related to the Key Thrust Areas, that have, or will have, the most significant impact on the engineering industry in New Zealand:

- Understanding the residual capacity of earthquake-damaged buildings and validating repair methodologies.
- Testing newly proposed detailing of structural elements targeted at addressing issues identified from the Christchurch earthquake.
- Seismic behaviour of non-structural elements
- New technologies for low-damage design
- Seismic loss assessment and new means of quantifying performance.

These are discussed in the subsequent sections of the paper, and in each case key pieces of research are identified along with the authors' views on why they are important to the industry.

UNDERSTANDING THE RESIDUAL CAPACITY OF EARTHQUAKE-DAMAGED BUILDINGS AND VALIDATING REPAIR METHODOLGIES

The 2010/2011 Canterbury Earthquakes Sequence resulted in damage to buildings on a scale not experienced in New Zealand since the 1931 Hawke's Bay Earthquake. Following the event, there was widespread need for the structural engineering community to both evaluate the residual capacity of buildings and, in the case that they were repairable, develop repair solutions. Anecdotal evidence suggests that most engineers had limited experience in assessing the residual capacity of buildings and there was a notable lack of guidance. Furthermore, there were numerous questions around the effectiveness of various repair solutions, particularly for cracked concrete. Flagship 4 research has made significant steps in addressing these gaps, so that engineers can be better prepared and have access to useful guidance the next time a damaging earthquake occurs. The key research contributions are summarised below.

Understanding Residual Capacity

Structures that undergo inelastic deformations during an earthquake may experience a reduction in capacity to resist future events. This can manifest itself as a reduction in strength, stiffness or low-cycle fatigue capacity in individual structural elements and the building as a whole. Understanding the residual capacity of a building is important for the post-earthquake decision making process as it may inform decisions as to whether a building needs repair work, is fine as is, or requires demolition. It may also be a factor in insurance claim processing.

Marder et al. [1] investigated the relationship between residual crack widths in reinforced concrete beams, peak drift demands, and reduction in stiffness. The study was based on a selection of beams from an experimental testing programme undertaken by Marder et al. [2]. Consideration was only given to moderately damaged beams (i.e. cracking, longitudinal steel yielding, cover concrete spalling); noting that it would be impractical to study highly damaged beams, which are unlikely to be reparable.

Various metrics for severity of cracking were related to peak drift, but it was observed that there was significant dispersion in the relationships. Therefore, the authors recommended that use of such relationships to estimate peak drift be supported by a numerical analysis of the structure. A relationship was then established between peak displacement ductility demand and reduction in stiffness. This QuakeCoRE funded research has also led to the FEMA funded ATC-145 project that aims to develop repair guidelines for earthquake damaged buildings [3,4].

Another useful finding from the same test data of Marder et al. [2] was that variations in cycle content of loading protocol at low drifts (less than 2%) had limited effect on ultimate deformation capacity and residual energy dissipation capacity [5].

Validating Repair Methodologies

Marder et al. [6] extended their previous research to investigate the effect of epoxy repair on plastic hinges in moderately damaged beams. Although a common repair solution for cracked concrete, many questions were asked around its effectiveness as a repair solution following the Canterbury earthquakes; particularly the question of whether it could fully restore the strength and stiffness of the damaged element. Data were obtained from three beam specimens tested by the researchers and past experimental campaigns by others. The research found that a 20% reduction in secant stiffness to yield was a reasonable lower bound for epoxy repaired beams and was independent of the ductility demand previously experienced. The flexural strength of epoxy repaired beams was found in cases to be up to 25% greater than the strength of identical undamaged beams, which the researchers attributed to strain ageing and/or higher levels of strain hardening in the longitudinal reinforcing. A recommendation was therefore made that caution be exercised when using epoxy repair solutions to check that an increased beam strength would not lead to an undesirable column-sway mechanism. Energy dissipation and deformation capacity in the epoxy repaired beams was generally found to be comparable to that of undamaged beams. It was also noted by the researchers that epoxy repair locks in residual axial elongations in the beams, and so cumulative elongation in subsequent earthquakes is larger.

Similar research was undertaken by Motter et al. [7] for reinforced concrete walls (see Figure 2). However, in this case the research focused on heavily damaged elements, and the repair solution involved more or less wholesale reconstruction of the damaged plastic hinge region. The repair solution involved breaking out the damage portion of the wall, replacing longitudinal reinforcing in the damaged region and welding into the remaining reinforcing in the undamaged regions, and then reinstating the wall section using repair mortar. Comparison of the behaviour to that of the walls in their pre-damaged state showed a reduction in stiffness of 33-50%; however, this was largely attributed to cracks in the "undamaged" region of the wall that were not repaired.

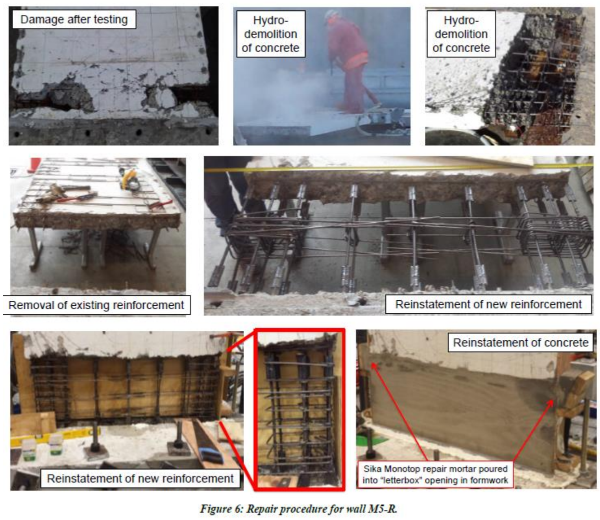

Figure 2: Repair procedure of a wall tested by Motter et al. [7].

The above research serves as a good starting point for engineers seeking to understand the residual strength and stiffness of reinforced concrete buildings following a strong earthquake and would thus be of use to engineers undertaking seismic assessments and developing repair solutions. It may also be useful in helping other stakeholders, such as insurance companies, in understanding losses incurred during an event. The research could help engineers in the design of new buildings as they seek to understand the repairability of their designs. One important aspect that appears to have been outside the scope of the research to date is the public perception of repaired earthquake-damaged buildings.

TESTING OF NEWLY PROPOSED DETAILING FOR STRUCTURAL ELEMENTS

It is common to find that post-event inspections after major earthquakes identify examples of structural detailing that have performed poorly or in an unexpected manner. One such observation following the Canterbury Earthquakes was the poor performance of RC wall buildings, many of which incurred significant damage and were subsequently demolished [8,9]. Blount et al. [10] undertook experimental testing on several details that had been proposed to address the issue of excessive damage and enhance repairability in the plastic hinge regions of lightly-reinforced RC walls. Four different modifications to plastic hinge detailing were tested, including debonding of reinforcement (DBR) at the wall base (see Figure 3), substituting fibre-reinforced concrete (FRC) for conventional concrete, and two different instances of substituting engineered cementitious composite (ECC) for conventional concrete in the ends of the plastic hinge region.

Figure 3: Close up of the debonding sleeves used in the experimental testing of Blount et al. [10]. Photo courtesy of Rick Henry.

The test specimens were subjected to a cyclic testing regime to increasing levels of drift and the results were compared to a benchmark specimen with conventional detailing. The DBR specimen used steel tubes to debond a length of longitudinal reinforcing into the foundation. This resulted in initially less damage as reinforcing strains were distributed over a reasonable length and cracking was restricted to a single location at the base of the wall. However, buckling of the reinforcing at high drifts resulted in sliding at the wall base as the deformed shape prevented the bar retracting freely into the steel tube; ultimately this led to a drift capacity no larger than the benchmark.

The FRC and ECC walls fell short of the researchers' expectations. They initially exhibited more cracking at low drift cycles, and then at large drifts, deformations were concentrated along a single dominant crack. This led to buckling of reinforcing and lower drift capacity than the benchmark. Recommendations were made that could potentially improve the performance of some of the modifications tested. For the DBR modification a telescoping sleeve was recommended while for the FRC detail an increased fibre volume ratio was proposed to improve tensile strain hardening (and presumably thus crack distribution).

The above research findings clearly illustrate the challenges around alternative detailing to improve seismic performance. In rebuilding following an earthquake there will clearly be a desire to not rebuild using techniques that were observed to perform poorly. However, this must be balanced against the risk of using untested detailing. Furthermore, in the case that such details might have been used in practice, engineers should review whether these might exhibit the same poor performance observed during testing. This research into better seismic detailing offers a very practical way to promote better collaboration between research and practice.

SEISMIC PERFORMANCE OF NON-STRUCTURAL ELEMENTS

It has been shown that non-structural elements can comprise in the order of 50-70% of the total cost of a building project, depending on the building type [11]. Historically, non-structural elements have not been specifically designed for seismic considerations, and therefore it is not surprising that they are a significant contributor to direct economic losses during earthquakes. Furthermore, damage to non-structural elements can cause significant business interruption due to the downtime required for repair, or through consequential damage (e.g. flooding from fire sprinkler pipes).

Although the need for improved seismic performance of non-structural elements has been acknowledged for some time, there are ongoing efforts required to deliver this.

Sullivan [12] provides an overview of the most recent developments in the New Zealand context. These include:

- Alternative solutions for drift-sensitive non-structural elements with significant lateral deformation capacity (prior to incurring damage).
- Consideration of factors affecting acceleration-sensitive non-structural elements: inadequate industry procurement processes, inaccurate estimation of floor acceleration demands, and lack of understanding of the behaviour and interactions of non-structural elements.
- The need to consider repairability during conceptual design and the role that non-structural elements have on repair costs.

Mulligan et al. [13,14] undertook experimental testing on two alternative partition wall solutions, aimed at reducing drift induced damage. The first solution used seismic gaps at the ends of the partition walls and allowed the framing to slide within the top and bottom tracks. The second solution used a partly-sliding steel-framed system, examined in the past and used by the industry. In both cases the solutions were able to achieve higher levels of drift, prior to sustaining damage, than conventional partition wall solutions. Similar experimental testing was undertaken by Arifin et al. [15] for commercial glazing systems, as shown in Figure 4. They observed that leaking of glazing initiated at a median story drift of 0.35% whereas glass breakage did not occur until a median drift of 5.0% Their conclusion was that modern commercial glazing systems are likely to pose a relatively low life-safety risk, but improvements could be made in terms of serviceability weathertightness. Sullivan [16] also suggests that changes should be made to the standards to ensure that some form of seismic testing of glazing systems becomes mandatory.

A key factor in achieving improved performance of acceleration sensitive non-structural elements is accurate estimation of floor acceleration demands. Haymes et al. [17] developed a practice-oriented method for predicting floor acceleration spectra, which built on previous efforts. The method described in [17] is limited to elastic response but was shown to give improved predictions over a number of current code-based methods. It is understood that progress for non-linear structural and non-structural response is also being made [18] with new recommendations expected this year.

Figure 4: Experimental test setup of Arifin et al. [15] used for testing watertightness of a commercial glazing system.

The impact that non-structural elements can have on the repairability of structures was examined by Sullivan et al. [19] and [20]. The researchers examined the repair of the 22-storey Pacific Tower in Christchurch after it was damaged during the Canterbury Earthquakes sequence. In the case of the replacement of a damaged EBF link, it was reported that decommissioning or rerouting of non-structural elements contributed to approximately half of the repair cost. It was recommended that repair methodologies for key structural elements be explicitly considered in design, which in turn may significantly reduce post-earthquake repair costs.

This body of research provides an important resource for designers. It is particularly useful as guidance for designers seeking to minimise damage to non-structural elements. It is anticipated that this research will help form the basis of industry guidance relating to low-damage design.

NEW TECHNOLOGIES FOR LOW-DAMAGE DESIGN

Although the concept of Low-Damage Design (LDD) has been around for several decades, it has recently come to the fore in New Zealand as a result of the Canterbury Earthquakes and other damaging events. Traditional ductile design philosophies used in Christchurch arguably achieved their performance objective of protecting life safety; however, the damage incurred resulted in the structures being uneconomical to repair

The Canterbury Earthquakes Royal Commission Vol. 3 [21] recommended that research continue into the development of low-damage technologies as a means of improving building performance during earthquakes. In this context, low-damage technologies are considered to be structural forms, systems, or devices that either supress damage or limit it to easily replaceable elements.

To have a tangible impact on the way we design and construct buildings, research must test the seismic performance of LDD devices and systems and provide appropriate design methods to get them from the lab into practice.

One particular device that has seen increased uptake in New Zealand is the fluid viscous damper. To support engineers in the design of buildings using such devices, Xie et al. [22] investigated the influence of damper sub-system stiffness on seismic response. The researchers reported that most design methods for sizing viscous dampers assume a rigid brace sub-system. However, flexibility in the damper sub-system can lead to increased displacements and base shears. Their research investigated these potential impacts and came to the practical design recommendation that designers should ensure the brace sub-system is five to 10 times the stiffness of the main lateral load resisting system (to treat it as effectively rigid).

System-level shake-table testing has also been undertaken on a two-storey low-damage concrete wall building (see Figure 5). The tests were completed on the Tongji University multifunctional shake-table array as part of a collaborative research project between QuakeCoRE and the International Joint Research Laboratory of Earthquake Engineering (ILEE). Henry et al. [23] report that the building performed

Figure 5: System-level shake-table testing of a two-storey low-damage concrete wall building. Photo courtesy of Rick Henry.

exceptionally well and has produced a rich dataset, which will presumably lead to design recommendations in future publications. This includes with regard to a number of details that have already been implemented in buildings in New Zealand, such as post-tensioned rocking walls and slotted beams.

In addition to the increased focus on low-damage design solutions, the industry is also currently experiencing a strong push towards more sustainable construction techniques – often with timber at the forefront. QuakeCoRE has contributed in this space through the research of Dong et al. [24,25], who looked at both the numerical modelling and experimental testing of glulam frames with buckling restrained braces. This research has been complemented by additional work from the same authors investigating the performance of glulam moment connections using self-drilling dowels [26].

For practitioners investigating innovate low-damage design solutions, the QuakeCoRE research can provide the basis and initial test data for their designs. Generally, the researchers are also willing and able to provide additional support to practitioners seeking to implement these solutions on projects.

SEISMIC LOSS ASSESSMENT AND NEW MEANS OF QUANTIFYING PERFORMANCE

A number of Flagship 4 researchers have undertaken loss-assessment studies to evaluate and compare the performance of various buildings. In particular, loss assessment has focused on estimating average annualised losses, with consideration given primarily to direct economic losses. Estimating average annualised losses allows for a fair comparison of building performance. Furthermore, it allows cost-benefit studies to be undertaken whereby stakeholders can evaluate whether additional upfront investment, for example in a low-damage design solution, is likely to be recovered during the life of the building. This type of assessment is illustrated in Yeow et al. [26], where the researchers investigated the cost effectiveness of using friction beam-column connections over traditional variants. Their net-present-cost analysis indicated that the time to return on investment was less than 7 years for their 4-storey architype buildings in Wellington and Christchurch but greater than 50-years for their 12-storey building in Auckland. This provides a convincing argument, from purely a seismic performance perspective, for when this particular connection detail might be adopted.

To undertake such studies, it is essential to have appropriate component fragility functions, which define the probability of experiencing a particular level of damage (Damage State) given a level of demand (e.g. inter-storey drift). Yeow et al. [28] evaluated a suite of existing fragility functions for their relevance to seismic loss assessment in New Zealand. Their study looked at key structural and non-structural components and proposed a number of modifications to existing fragility functions for easier use in practice. They also recommended that where New Zealand specific fragility functions are not readily available, other fragility functions can be used as placeholders, noting that the overall impact on calculated losses was not found to be substantial in their examples.

Another key component to performing seismic loss assessment is consequence functions, which define likely consequences (e.g. repair costs, repair time, fatalities) for a given level of damage to a component. Additional Flagship 4 research is underway, with initial data available on Design Safe [29], to establish repair costs for structural and non-structural elements in various damage states. This work draws on experience from the Christchurch Earthquake and, in particular, seeks to identify some of the factors that may lead to unexpectedly large costs. For example, removing non-structural linings to access structural elements. Ultimately, this research aims to provide NZ specific repair costs than can be utilised in loss-assessment projects.

It is the authors' view that seismic loss assessment is unlikely to see widespread direct adoption by the industry in the short term. However, studies comparing the performance of different structural systems (e.g. [27]) are likely to influence engineers in the design decisions that they make and the discussions they have with clients. There would be benefit in future work making this loss assessment data more easily accessible to designers, and to other building stakeholders.

CONCLUSIONS

The authors' have undertaken a review of the research produced as part of the QuakeCoRE Flagship Programme 4. Based on this review, engagement with Flagship 4 leadership, and experience in the industry, the authors determined that the key areas where Flagship 4 was likely to have an impact on the industry were:

- Understanding the residual capacity of earthquake-damaged buildings and validating repair methodologies.
- Testing newly proposed detailing of structural elements targeted at addressing issues identified from the Christchurch earthquake.
- Seismic behaviour of non-structural elements
- New technologies for low-damage design
- Seismic loss assessment and new means of quantifying performance.

The research outputs make a meaningful contribution to addressing needs identified from the Christchurch Earthquake and other major events of the last decade. However, there remain gaps where further research is required and results from more recent work, particularly experimental testing, still require dissemination. As noted previously, QuakeCoRE has been refunded through to 2028, allowing research to continue and providing opportunity for further industry engagement.

REFERENCES

1 Marder K, Elwood KJ, Motter CJ and Clifton GC (2020). "Post-earthquake assessment of moderately-damaged reinforced concrete plastic hinges". *Earthquake Spectra*, **36**(1): 299-321. https://doi.org/10.1177/8755293019878192

2 Marder K, Motter CJ, Elwood KJ and Clifton GC (2018). "Testing of 17 identical ductile reinforced concrete beams with various loading protocols and boundary conditions". *Earthquake Spectra*, **34**(3): 1025-1049. https://doi.org/10.1193/101717EQS215DP

3 Henry RC, *Personal Communication*, September 2021.

4 Elwood KJ, Sarrafzadeh M, Pujol S, Liel A, Murray P, Shah P and Brooke NJ (2021). "Impact of prior shaking on earthquake response and repair requirements for structures – studies from ATC-145". *Proceedings of the 2021 NZSEE Conference*, Christchurch, New Zealand.

5 Marder K, Motter CJ, Elwood KJ and Clifton GC (2018). "Effects of variation in loading protocol on the strength and deformation capacity of ductile reinforced concrete beams". *Earthquake Engineering and Structural Dynamics*, **47**(11): 2195-2213**.** https://doi.org/10.1002/eqe.3064

6 Marder K, Elwood KJ, Motter CJ and Clifton GC (2019). "Quantifying the effects of epoxy repair on reinforced concrete plastic hinges". *Bulletin of the New Zealand Society for Earthquake Engineering*, **53**(1): 37-51. https://doi.org/10.5459/bnzsee.53.1.37-51

7 Motter CJ, Clauson AB, Petch JC, Hube MA, Henry RS and Elwood KJ (2017). "Seismic performance of repaired lightly-reinforced concrete walls". *Bulletin of the New Zealand Society for Earthquake Engineering*, **50**(4): 574-585. https://doi.org/10.5459/bnzsee.50.4.574-585

8 Kam WY, Pampanin S and Elwood KJ (2011). "Seismic performance of reinforced concrete buildings in the 22 February Christchurch (Lyttelton) Earthquake". *Bulletin of the New Zealand Society for Earthquake Engineering*, **44**(4): 239–278. https://doi.org/10.5459/bnzsee.44.4.239-278

9 Sritharan S, Beyer K, Henry RS, Chai YH, Kowalsky M and Bull D (2014). "Understanding poor seismic performance of concrete walls and design implications". *Earthquake Spectra*, **30**(1): 307–34. https://doi.org/10.1193/021713EQS036M

10 Blount SW, Ryan KL, Henry RS, Lu Y and Elwood KH (2020). "Evaluation of design modifications for enhanced repairability of reinforced concrete walls". *Engineering Structures*, **206**: 110034. https://doi.org/10.1016/j.engstruct.2019.110034

11 Taghavi S, Miranda E (2003). "*Response Assessment of Nonstructural Building Elements"*. PEER Report 2003/5 Pacific Earthquake Engineering Research Center, College of Engineering, University of California Berkeley.

12 Sullivan TJ (2020). "Post-earthquake reparability of buildings: the role of non-structural elements". *Structural Engineering International*, **30**(2): 217-223. https://doi.org/10.1080/10168664.2020.1724525

13 Mulligan J, Sullivan TJ and Dhakal RP (2020). "Experimental study of the seismic performance of plasterboard partition walls with seismic gaps". *Bulletin of the New Zealand Society for Earthquake Engineering*, **53**(4): 175-188. https://doi.org/10.5459/bnzsee.53.4.175-188

14 Mulligan J, Sullivan TJ and Dhakal RP (2020). "Experimental seismic performance of partly-sliding partition walls". *Journal of Earthquake Engineering*. https://doi.org/10.1080/13632469.2020.1733139

15 Arifin AF, Sullivan TJ and Dhakal RP (2020). "Experimental investigation into the seismic fragility of a commercial glazing system". *Bulletin of the New Zealand Society for Earthquake Engineering*, **53**(3): 144-149. https://doi.org/10.5459/bnzsee.53.3.144-149

16 Sullivan TJ (2021). "Earthquakes and leaky buildings". *BRANZ Build Magazine*, **183**: 54-55.

17 Haymes K, Sullivan TJ and Chandramohan R (2020). "A practice-oriented method for estimating elastic floor response spectra". *Bulletin of the New Zealand Society for Earthquake Engineering*, **53**(3): 116-136. https://doi.org/10.5459/bnzsee.53.3.116-136

18 Haymes K, Sullivan TJ and Chandramohan R (2021). "Strength requirements for non-structural components responding nonlinearly under earthquake excitation". *Proceedings of the 2021 NZSEE Conference*, Christchurch, New Zealand.

19 Sullivan TJ, Arifin FA, MacRae GA, Kurata M and Takeda T (2018). "Cost-effective consideration of non-structural elements: lessons from the Canterbury earthquakes". *Proceedings of the 16th European Conference on Earthquake Engineering*, Thessaloniki, Greece.

20 Arifin FA, Sullivan TJ, MacRae G, Kurata M and Takeda T (2021). "Lessons for loss assessment from the Canterbury earthquakes: A 22-storey building". *Bulletin of Earthquake Engineering*, **19**: 2081-2104. https://doi.org/10.1007/s10518-021-01055-7

21 Canterbury Earthquakes Royal Commission. *Final Report Volume 3 Low-Damage Building Technologies*.

22 Xie RM, Rodgers GW and Sullivan TJ (2019). "Effect of damper sub-system stiffness on the response of a single degree of freedom system equipped with a viscous damper". *Journal of Earthquake Engineering*. https://doi.org/10.1080/13632469.2021.1911879

23 Henry RS, Zhou Y, Lu Y, Rodgers GW, Gu A, Elwood KJ and Yang TY (2021). "Shake-table test of a two-storey low-damage concrete wall building". *Earthquake Engineering and Structural Dynamics*, **50**(12): 3160-3183. https://doi.org/10.1002/eqe.3504

24 Dong W, Li M, Lee CL and MacRae G (2021). "Numerical modelling of glulam frames with buckling restrained braces". *Engineering Structures*, **239**: 112338. https://doi.org/10.1016/j.engstruct.2021.112338

25 Dong W, Li M, Lee CL, MacRae G and Abu A (2021). "Experimental testing of full-scale glulam frames with buckling restrained braces". *Engineering Structures*, **222**: 111081. https://doi.org/10.1016/j.engstruct.2020.111081

26 Dong W, Li M, Lee CL, MacRae G and Abu A (2021). "Experimental testing and analytical modeling of glulam moment connections with self-drilling dowels". *Journal of Structural Engineering*, **147**(5). https://doi.org/10.1061/(ASCE)ST.1943-541X.0002977

27 Yeow TJ, Orumiyehei A, Sullivan TJ, MacRae GA, Clifton GC and Elwood KJ (2018). "Seismic performance of steel friction connections considering direct-repair costs". *Bulletin of Earthquake Engineering*, **16**: 5963-5993. https://doi.org/10.1007/s10518-018-0421-x

28 Yeow TJ, Sullivan TJ and Elwood KJ (2018). "Evaluation of fragility functions with potential relevance for use in New Zealand". *Bulletin of the New Zealand Society for Earthquake Engineering*, **51**(3): 127-144. https://doi.org/10.5459/bnzsee.51.3.127-144

29 Fox MJ, Goebbels S, Keen J and Sullivan TJ (2021). "*Repair Methods and Costs for Earthquake-Damaged Building Components in NZ*". https://www.designsafe-ci.org/data/browser/public/designsafe.storage.published/PRJ-3126