Seismic Restraint of non-structural elements – evolving design thinking

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ABSTRACT

Seismic Restraint of non-structural elements has received increased attention in the past decade within the New Zealand building industry. Clients and Project Managers are now often coupling Seismic Restraint design with the base build Structural Engineer's scope, requiring an upskilling in this area for most.

This paper describes some of the technical challenges we have encountered in designing Seismic Restraint of non-structural elements which, in many instances, fall outside the scope of the Verification Methods of the New Zealand Building Code.

We also summarise some of the practical challenges we've faced in inserting this design service into typical building design workflows. There are different ways to implement Seismic Restraint design – each with its own set of risks and opportunities, and each needing to be tailored to suit individual project (and project team) needs and to achieve desired outcomes.

We outline areas of Seismic Restraint design practice we would like to see improved in response to these challenges, as well as recommendations for research to improve the performance of non-structural elements in future earthquakes.

1 INTRODUCTION

Seismic Restraint of non-structural elements (NSE) has received a lot of attention, especially in the past decade, due to several factors (Stanway, 2022). The Canterbury and Kaikoura earthquakes demonstrated our building stock is generally quite resilient; however, many buildings suffered from the effects of failures of NSE (Baird et al, 2014). Several newer buildings built after the earthquakes, had their Seismic Restraint of NSE designed late (often during construction) and/or by multiple parties, which resulted in less-than-ideal outcomes for Clients and Contractors.

In response to these poor outcomes, educational institutions have spent time, money, and energy on new research into the seismic performance of NSE to better understand the issues and test new solutions (Rashid et al, 2021). In the same period, the New Zealand building industry has responded by asking Structural Engineers to take on Seismic Restraint of NSE within their primary structural design scope. This new Seismic Restraint scope has required an upskilling for many engineers – from understanding the complexities associated with drift and acceleration-sensitive NSE (AWCI, 2018) to appreciating the practical implications of inserting early Seismic Restraint design into traditional design workflows and becoming familiar with overlaps and discrepancies between the various New Zealand building standards which address this topic.

2 TECHNICAL CHALLENGES UNCOVERED

2.1 Compliance pathways

2.1.1 Seismic Restraint of services

Seismic Restraint of services has a compliance pathway, as B1/VM1 references the NZS4219 (Standards NZ 2009) standard 'Seismic performance of engineering systems in buildings'. This standard covers nonspecific and specific engineering design of Seismic Restraint systems for typical mechanical, hydraulic, and electrical services within a building. The process of determining loads is similar to the NZS1170.5 (Standards NZ 2004) Parts and Components process with some simplifications built in.

NZS4219 has some helpful tables to ensure steel and copper pipes can span between transverse and longitudinal restraint points for 1g, 2g and 3.6g accelerations. The commentary clause notes assumptions regarding deflection and stress limits as well as assumptions from which the tables were derived. In clause 3.6, ducts, pipes and cable trays are mentioned, but the standard doesn't provide similar guidance on their self-spanning capacity between restraint points. These shortcomings can lead to inconsistencies in approach as has been outlined previously (Egbelakin et al, 2018). To bridge the gap for duct spans, we have utilised Practical Guide to Seismic Restraint (Tauby and Lloyd, 2012), which is referenced in NZS4219. This publication has guidance on the self-spanning capacity of ducts for varying earthquake accelerations, which appears to be an appropriate Alternative Solution to meet the intent of B1. We haven't been able to find suitable guidance on the self-spanning capacity of cable trays within New Zealand standards or guidance documents and, thus, we have referenced International Seismic Application Technology (ISAT) Seismic Restraint Systems Guidelines (ISAT, 2013).

2.1.2 Seismic Restraint of suspended ceilings

Seismic Restraint of suspended ceilings is addressed by the standard AS/NZS 2785 (Standards NZ, 2020). This standard is not currently cited as a verification method under B1. It provides good guidance on the principles related to restraining suspended ceilings, however, it doesn't align with other NZ standards such as NS1170.5. AS/NZS2785 requires suspended ceilings within NZ to be designed for elastic (mu=1.0) Parts and Components accelerations determined in accordance with NZS1170.5. NZS1170.5 commentary Table C8.2 suggests ductilities of 2-3 are appropriate, depending on support conditions. Ultimate Limit State (ULS) is listed in AS/NZS2785 as a design load case and notes the ceiling must maintain equilibrium at this load level, whereas NZS1170.5 commentary table C8.1 lists light suspended ceilings as an example of the P.7 Parts Category. This reveals an inconsistency, as following AS/NZS2785 requires design to ULS, while following NZS1170.5 appears to only require design to SLS1.

Given the life safety hazard suspended ceilings present to occupants of buildings, and recent examples of poor performance, we recommend designers design suspended ceiling restraint systems and check ceiling components to maintain equilibrium at ULS loads.

2.1.3 Seismic Restraint of lightweight partition walls

Seismic Restraint of lightweight partitions doesn't have its own dedicated standard and, thus, falls under NZS1170.5 as a Part or Component. The NZS1170.5 commentary Table C8.2 suggests a ductility of up to 3 is appropriate for these Parts. We assume the standard is allowing for mechanisms other than yielding and plasticity for this suggested ductility, given timber studs (for instance) are likely to exhibit brittle failure once maximum bending stresses are exceeded. In our experience, it is stiffness, not strength, that often governs stud sizing and material choice. As such, the onset of damage to the finish material from face loading or in-plane loading is a more important consideration.

2.2 Design and detailing to avoid damage

Deflection head channels are standard in modern detailing of lightweight partition walls to provide damage protection from differential vertical floor movements. A correctly designed and detailed deflection head channel also provides a degree of damage protection for movements both in-plane (parallel to wall) and out-of-plane (perpendicular to wall) as the primary structure drifts in response to lateral loads.

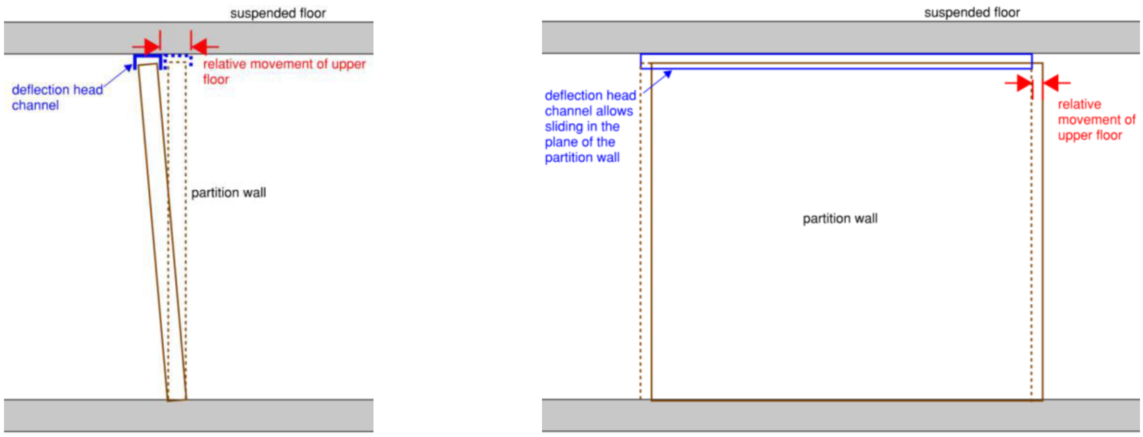

Figure 1. Cross section through partition wall subjected to interstorey drift perpendicular to wall (left), elevation of partition wall subjected to interstorey drift parallel to wall (right)

At the intersection of return walls, the out-of-plane restraint to these partition walls conflicts with the in-plane movement allowance as the lower wall segment moves relative to the upper segment, as illustrated in Figure 2 below.

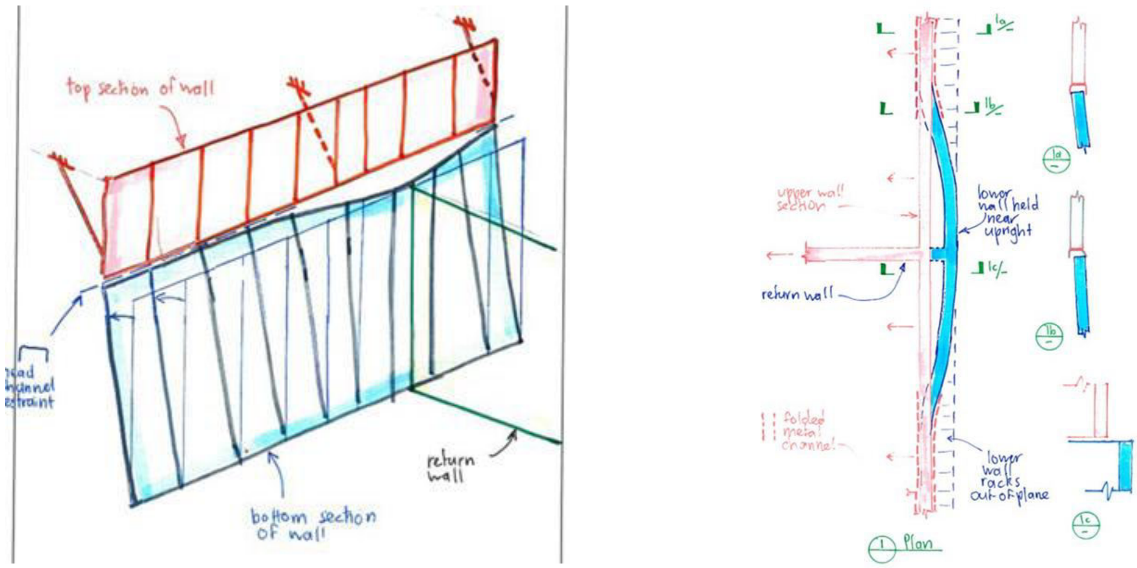

Figure 2. Interstorey drift allowance at return wall intersections

To provide a better level of damage protection at intersecting walls, we have terminated the deflection head channel and/or the out-of-plane restraints ~1.5m from the intersection with the return wall to allow flexibility at this interface. A similar approach has been tested (Mulligan et al, 2020) by removing anchor bolts within 600mm of the intersection. The experiments showed improved performance at the intersection; however, we would anticipate even better results with an increased offset of restraint to the intersecting walls. There is also precedence within guidance (Tracklok, 2022) for proprietary partition wall restraints in the industry; however, this guidance appears to be limited to lower drift buildings.

Other research (Tasligedik et al, 2015) looked at vertical and horizontal gaps within gypsum lined walls as well as connecting linings to studs only. These tests showed walls remained undamaged to relatively high drifts, however there are limitations to this type of detailing. One example is partition detailing in hospitals where SLS2 criteria is required by the building code for IL4 buildings, but infection control considerations will most likely not allow gaps in plasterboard.

2.3 Post-installed anchors

Designing compliant post-installed anchors as part of Seismic Restraint systems has proved very challenging (Castillo & Ingham, 2019). Least challenging are the requirements of NZS4219 which allow the use of post-installed anchors certified to ACI 355.2 (American Concrete Institute, 2019) – understood to be similar to C1 rating to ETAG 001 Annex E (EOTA, 2012) (now superseded by EN 1992-4 (Eurocode, 2018)). Much more challenging is design of post-installed anchors restraining lightweight partition walls and suspended ceilings. Design of post-installed anchors should be in accordance with NZS3101 (Standards NZ, 2006) which, under Clause 17.5.5, requires C2-rated anchors due to New Zealand's peak ground accelerations exceeding the 0.1g threshold. Unfortunately, very few modern floor systems, including composite metal deck, have an option for C2-rated anchoring systems. Therefore, designers have limited options for selection of compliant anchors (e.g., through anchors with washers). Left with limited practical options, designers appear to regularly specify non-compliant C1-rated anchors. For the specific case of retrofitting Seismic Restraint in existing buildings with hollow-core flooring systems, there appears to be no C1 or C2-rated anchoring systems available.

3 PRACTICAL CHALLENGES UNCOVERED

3.1 Seismic Restraint design during preconstruction phase

In New Zealand, Seismic Restraint of NSE has traditionally been passed on to the Contractors to complete in the pre-construction or construction phase. There are two key risks we have observed with this approach – 1) fitout coordination challenges faced by services subcontractors, and 2) significant diminished opportunity to influence an economic Seismic Restraint design solution.

Seismic Restraint design for reticulated services is often provided by the individual subcontractor's preferred engineer. This can mean three or more different engineers are providing Seismic Restraint design for services on a single project. These engineers are likely not considering services other than their own, nor the associated gravity restraints or Seismic Restraints – and are even less likely to consider the other in-ceiling NSE competing for space. Contractors tasked with coordination of Seismic Restraints are often managing multiple NSE and their associated designs, trying to ensure it all fits within the ceiling with required clearances. We have heard of instances where services and their associated gravity hangers and restraints have had to be deconstructed and moved during construction as there was simply not enough space within the ceiling plenum to accommodate all services and fit-out elements (and the Seismic Restraints that go along with them). The time and cost associated with these late changes is extreme and is generally borne either by the Contractor or Client.

It is a well understood principle the earlier a design change is implemented, the less cost impact that design change will have on the project – refer Figure 3. Therefore, if significant changes are required to achieve a compliant Seismic Restraint design late in the process, we would expect a significant associated cost for that change.

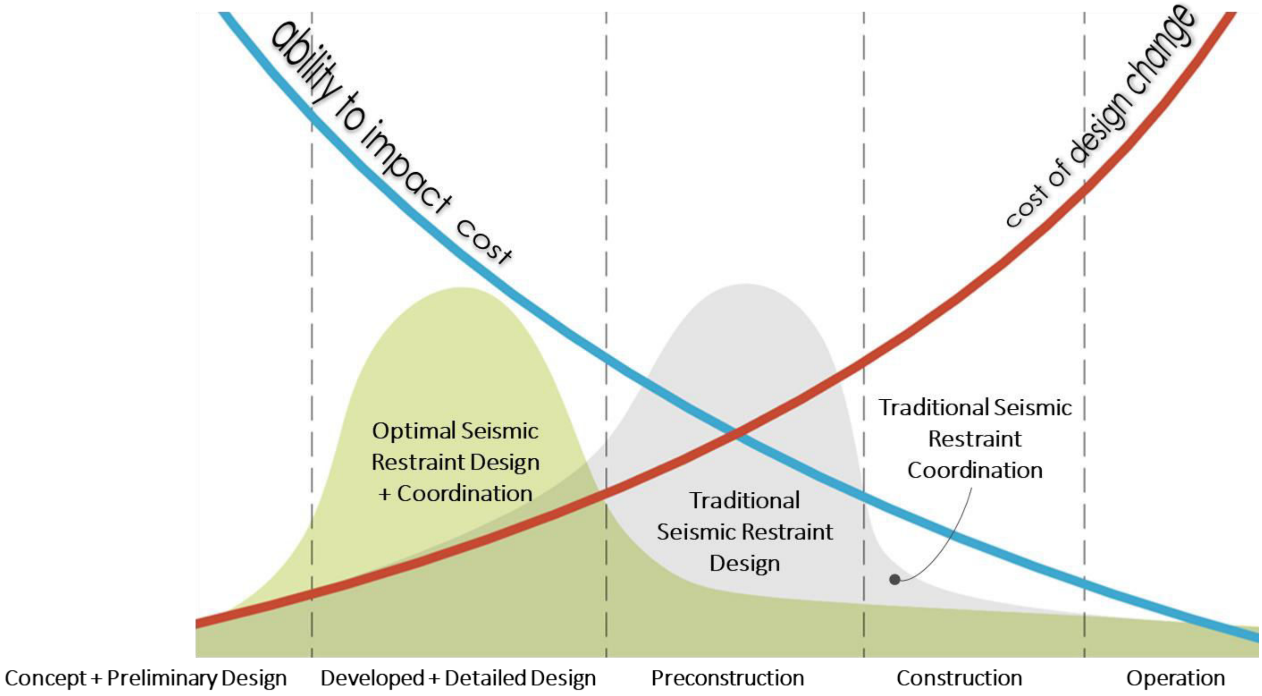

Figure 3. Traditional versus optimal Seismic Restraint Design and coordination and the influence over design cost

In some instances (and for some building types), design of Seismic Restraint during the preconstruction or construction phase does have its advantages. One key advantage is that the architectural and services designs are fixed and, thus, the risk of rework to the Seismic Restraint designer is low. For relatively simple buildings which are lightly serviced and tend not to have congested in-ceiling spaces (e.g., traditional office buildings), the risk of Contractor-led Seismic Restraint design during preconstruction or construction is much less. These building types allow relative freedom for subcontractors to locate reticulated services and their associated Seismic Restraints away from partition walls and suspended ceiling braces and, thus, provide an environment where a constructable solution is much more likely to be achievable if flexibility is built into the Seismic Restraint design, rather than delivering a rigidly coordinated solution.

3.2 Seismic Restraint design during base build design phase

More recently, Clients and Project Managers have requested Seismic Restraint of NSE be undertaken by the Structural Engineer during the base build design phase. On the surface, this approach may appear obvious and straightforward; however, we have found it to be much more challenging to implement effectively and efficiently than we had originally envisioned. The key risk to this early design approach is that architectural and services designs are very iterative and thus Seismic Restraint designers can be subject to costly rework from design changes. However, if we don't design Seismic Restraint early and work through the coordination issues, we limit our ability to implement a cost effective and efficient Seismic Restraint design solution.

Similar to primary structural design, every building/structure is different, but there are common themes that run through each which we can use our experience to navigate. We observe that services congestion increases around vertical risers and within plant rooms as ducts, pipes and cable trays travel from the rooms they are servicing back to the plant equipment. Therefore, focusing time and energy in these areas during the earlier design phases can provide the positive influence we are targeting to these areas of the project.

Another key lesson we have learned is how sensitive various NSE are to their plan location. For example, the Architect locates a part-height partition wall on plan to define the edge of a room. The Seismic Restraint designer would then, ideally, place the out-of-plane restraint to that part-height wall directly above it using an economical solution. However, if that wall restraint solution hasn't been included in the 3D model, it is likely the space will be used for reticulating services because the Services Engineers simply weren't aware of its existence. If we model these Seismic Restraint elements relatively early in the design process, we can mitigate rework in later design phases which will, ultimately, lead to a more economical and efficient design solution.

Like the part-height partition wall restraint outlined in the paragraph above, we have learned suspended ceiling back-braces to grid and tile ceilings are particularly sensitive to the intersection of those bracing elements with the ceiling grid. An example is shown below in Figure 4 below for a suspended ceiling, pointing out that the back-brace needs to fall within 50mm of the joint where the main runner intersects the cross tee to comply with the proprietary manufacturer's design guidance. If the Seismic Restraint designer can locate these elements within the model space early in the design process, the Services Engineers have the opportunity to locate their services to avoid these back-braces (or as many of them as possible), resulting in a higher quality, more constructible, more affordable and much less compromised Seismic Restraint design.

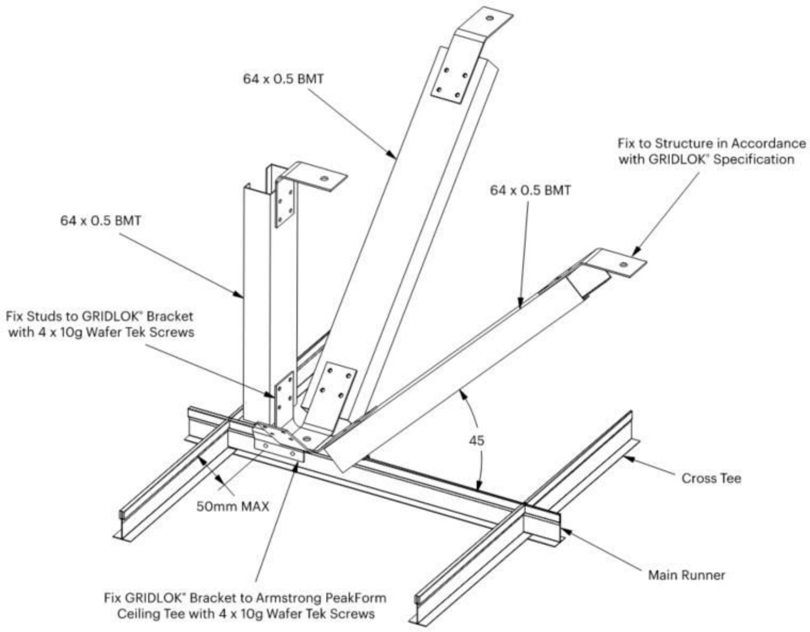

Figure 4. Low tolerance for Seismic Restraint to ceiling grid (source Armstrong Seismic Design & Installation Guide 2021:V12)

4 RECOMMENDATIONS FOR FUTURE RESEARCH AND IMPROVEMENTS

4.1 Restraint of non-structural elements to lightweight roofs

When building services, suspended ceilings and partitions are to be seismically restrained by lightweight roofs, special consideration is required to avoid overload of the roof structure (both globally, and locally). We recommend an appropriate allowance for the weight of these elements is made when the roof is designed by the base build Structural Engineer and details of this are recorded in the Design Features Report (DFR).

When designing and detailing the restraint of NSE, the Seismic Restraint specialist should ensure the base structure has adequate capacity to resist the design actions associated with those NSE.

The practice of relying on the out-of-plane capacity of light gauge purlins to resist Seismic Restraint design actions is not recommended (refer Figure 5). Light gauge purlins generally have little ability to resist out-of-plane loads and the light gauge steel sheet has a low bending capacity to resist connection forces applied in any orientation other than direct in-plane shear through the major axis of the purlin. Avoiding the unreliable load paths of weak axis bending or eccentric loading to purlins generally means additional elements will be required to transfer horizontal brace forces into the main roof bracing system.

Figure 5. Connecting Seismic Restraint braces to light gauge purlins

4.2 Compliant post-installed anchoring systems

As outlined above in Section 2.3, compliant post-installed anchoring systems are often unavailable for some conventional floor systems. Further seismic testing is required to cover common floor systems such that specifiers have compliant anchoring systems for their new or retrofit Seismic Restraint designs.

We recommend that further research be undertaken for post-installed anchoring products and whether a C1/C2 rating should be determined based on PGA alone. Given common practice in New Zealand is to design floor diaphragms to remain elastic at the overstrength accelerations of the vertical lateral load resisting system, it appears conservative to require the higher specification C2 anchors. Generally, NSE have relatively high redundancy and, if designers avoid potential plastic hinge zones in the primary structure, lower specification C1 or ACI355.2 (ACI, 2019) anchors may be more appropriate to balance cost versus risk.

4.3 Expansion of NZS4219 using international guidance

As noted in Section 2.1.1 above, NZS4219 (Standards NZ, 2009) only contains self-spanning guidance for steel and copper pipes. We recommend research be undertaken to establish the self-spanning capacities for all commonly reticulated services including, but not limited to, mechanical ducts, PVC pipes, stainless steel pipes and cable trays/ladders. This will improve the consistency of our approach to Seismic Restraint for these systems in New Zealand.

4.4 Consistency across NZ standards

Section 2.1 raises a common issue of inconsistencies between New Zealand Standards. A more consistent approach to allowable ductility and deformation limits (among other design considerations) across all NSE would be helpful to ensure equivalent resilience for these elements within buildings. We would also recommend more clarity be provided to deformation performance limits of NSE for achieving “life safety”, “no repair” and “operational continuity” design of Ultimate Limit State (ULS) and Serviceability Limit States (SLS1 & SLS2), respectively.

4.5 More guidance on achieving low damage designs

Following the recent earthquakes in Canterbury and Kaikoura, which had significant downtime while interiors were repaired, we have seen an increasing number of RFP/Qs and Client briefs that incorporate a

Damage Control Limit State between SLS1 and ULS, where low to no damage to the interior is expected. This performance requirement will often drive the primary lateral load resisting structure to a low drift solution (typically less than 0.5%) at this limit state, in accordance with international and national best practice. Some damage to lightweight partitions is still expected at this low drift level, however it will be limited to a manageable level and much improved when compared to a high drift structure.

We recommend further research be undertaken into the post-earthquake fire performance of modern lightweight partition walls when subjected to varying levels of drift. Previous research (Collier, 2005) showed significant reductions in fire performance when gypsum lined walls are subjected to full racking, however more modern detailing may supress this reduction in performance. We anticipate there is a interstorey drift limit at which well detailed (deflection head slip plane and return wall offset seismic restraints) partitions can still perform to an acceptable level to satisfy continued operation SLS2/DCLS performance targets.

We recommend further research be undertaken related to service penetrations through fire walls, as many passive fire solutions commonly used in New Zealand to treat those penetrations (e.g., fire collars and dampers) may not be capable of accommodating the anticipated earthquake movements. The relative direction and magnitude of those expected drifts will be influenced by the position of the penetration relative to the horizontal slip plane within the fire wall. Thus, given there is limited information on how well fire collars perform in earthquakes, designers are sometimes introducing a horizontal slip joint when one might not be needed, depending on the performance targets required by the project. We recommend more testing be undertaken to provide a better understanding of acceptable drifts for services penetrating fire walls under an SLS2/DCLS event, to maintain the operational capacity of the building.

5 CONCLUSIONS

As more Structural Engineers adapt to including Seismic Restraint in their base structural design offering, an upskilling has been required.

We have encountered many technical challenges in delivering this design service, including lack of clear compliance pathways, uncertainty on what drift levels require us to detail for differential movement at partition wall intersections, inconsistent performance limit states and ductility assumptions, inability to specify compliant post-installed anchor solutions and lack of guidance on how services self-span between Seismic Restraints.

We have also discovered practical implementation challenges, given the building design and construction industry is still adapting to the integration of Seismic Restraint design and coordination into the base build design phase of projects.

We see opportunities for improvement within both the technical and practical realms of Seismic Restraint delivery, and have offered suggested focus areas to support those improvements, with the aim of elevating the quality, consistency, constructability, cost effectiveness and performance of Seismic Restraint solutions in New Zealand.

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