Recommended practice for seismic restraint design of suspended ceilings

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ABSTRACT

Seismic restraint of suspended ceilings in the New Zealand environment has seen significant evolution over the past decade. Amendments to NZS1170.5 and updates to AS/NZS2785 are intended to drive better earthquake resilience for suspended ceilings, however neither the amendment nor the suspended ceiling standard have been cited by the New Zealand Building Code. Varying interpretation of these standards can lead to inconsistent design and performance of suspended ceilings.

There is a different global system behaviour between grid and tile ceilings, which are flexible in nature and more vulnerable to damage from vertical accelerations, versus plasterboard lined suspended ceilings that are stiffer when subjected to horizontal and vertical accelerations. Designers of grid and tile ceilings should be cognisant of the general lack of understanding (both nationally and internationally) of the seismic performance of these ceiling systems as a result of minimal shake table testing undertaken that incorporates both horizontal and vertical accelerations. This paper discusses the global system behaviour of both fully floating grid and tile and plasterboard lined suspended ceilings and provides guidance on load paths and design of individual members and connections.

Most suspended ceilings are built using manufacturer specific proprietary components which are assembled into an overall suspended ceiling system. To ensure designers can be satisfied these proprietary components have adequate strength and stiffness this paper also provides recommendations for specification clauses which are expected to provide more consistency through the industry and ensure supplier test data verifies member and connection capacities.

1 INTRODUCTION

Seismic Restraint of suspended ceilings in the New Zealand environment has seen significant evolution over the past decade. Amendments to NZS1170.5 (Standards NZ, 2016) and updates to AS/NZS2785 (Australian/New Zealand Standard, 2020) are intended to drive better earthquake resilience for suspended ceilings, however neither the amendments nor the suspended ceilings standard have been cited.

The authors have observed varying interpretations of these standards between different practicing professionals leading to inconsistency in design and their expected performance in future earthquakes. As noted in several papers (Pourali et al, 2014), (Dhakal et al, 2016), (Long et al, 2023), the cited standard requires design for SLS only in a lot of instances, when the gap between serviceable performance and life safety performance is very small.

2 EVOLUTION OF SUSPENDED CEILING STANDARDS

While there has been recent focus on suspended ceilings in New Zealand as a result of the significant damage sustained by these systems in the significant earthquake events that have occurred in New Zealand over the last 15 years, the concerns associated with them have been noted in several papers and reports dating back to the 1970’s (Glogau et al, 1979, Rihal, 1984). Many of the concepts and restraint methodologies proposed in these papers are still being used today.

Suspended ceilings became increasingly popular during the 1960s to provide a fast and cost-effective way to meet a wide range of architectural and services requirements (Glogau et al, 1979). However, it wasn't until the loading standard NZS 4203 (Standards NZ, 1976) was revised in 1976 that provisions were added specific to the design of suspended ceilings. Overseas, specific seismic installation guidance for suspended ceilings is directly referenced in the International Building Code. ASTM E580/E580M provides a means of achieving a minimum level of seismic compliance using construction methods that contractors were already familiar with.

Despite these requirements, substantial damage sustained by suspended ceilings during recent earthquakes highlighted systematic problems resulting in significant changes in the industry, particularly in New Zealand (Dhakal 2011). These changes were driven primarily by council consent requirements but also significant revisions to two of the relevant standards applicable to the design of suspended ceilings (Long et al, 2023):

- AS/NZS 2785; the principal ceiling design standard (although not directly referenced by the building code),
- NZS 1170.5; the seismic loading design standard.

The intention of these changes was to drive improved performance of these systems in earthquakes but a lack of direct adoption into the NZBC along with inconsistencies between the standards resulted in significant variations between the design approaches taken by different engineers. Coupled with the rapid changes to consenting requirements, this meant many of the adopted solutions were based on first principles rather than tested solutions as is common in other jurisdictions. In particular, fully floating ceilings with high strength, sparsely spaced seismic back bracing is now commonplace throughout New Zealand. This is directly in contrast to ASTM E580 that requires all ceilings to include two fixed edges along with regularly spaced back bracing for larger ceiling areas. Importantly, designers should recognise that recent testing on these ceilings has shown that they respond quite differently to those designed in accordance with ASTM E580 and testing associated with this is not directly applicable to fully floating braced ceilings (Long et al, 2023).

3 GLOBAL AND LOCAL BEHAVIOUR OF SUSPENDED CEILINGS

Whilst all ground shaking is multi-directional, the vertical component of shaking is generally accepted as being able to be accommodated by the structure’s gravity load resisting system, however in contrast acceleration sensitive non-structural elements are usually sensitive to both horizontal and vertical accelerations. Suspended ceilings are among the more vulnerable multi-directional acceleration sensitive non-structural components and despite the extensive damage observed in past earthquakes, there is still a lack of thorough investigation on the understanding of the behaviour and failure mechanisms, in particular of suspended grid and tile ceilings, during earthquakes.

Interestingly, Guzman Pujols et al (2020) used modelling techniques validated by the E-Defence test and found slab vertical amplification factors in a 3-storey moment frame building varied from 2.5 to 6.5, and from that they recommended a factor of 4 or 5 to be applied in design to determine vertical accelerations.

Response of grid and tile suspended ceilings

When grid and tile ceilings are subjected to horizontal accelerations during earthquakes the inertia of the ceiling tiles and grid support system move until restraint systems (i.e. Perimeter wall connections or back braces) arrest the movement. Ceiling tiles are laid onto the grid support system with no positive connection and have small gaps, therefore deformation as indicated in the Figure 1 below is required for the tiles to move and bear against the grid system. For edge restrained systems the load path is direct through the grid to the fixed edge. In the case of floating ceilings, the movement forces the tiles to “lock-up” and form a flexible diaphragm system to distribute forces to back braces.

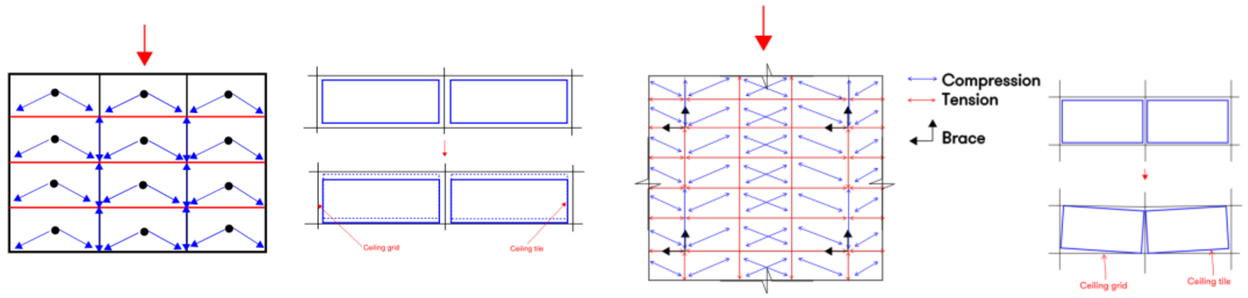

Figure 1. Examples of force flow from grid and tiles to restraint systems to highlight key differences, Perimeter fixed (left), Fully floating back braced (right)

As these effects can be difficult to quantify through calculation (also noting that suspended ceilings are not structural systems), testing has historically been used to define acceptable ceiling extents and weights for different restraint configurations under various levels of design seismic acceleration. Numerous shake table tests on suspended ceilings were carried out as part of the NEES Grand Challenge Project, which compiled results from previous research and additional testing to develop fragility curves for different non-structural elements. This research indicated that properly designed ceilings could maintain integrity at high levels of shaking even after some tile loss and grid damage had occurred (Badillo, 2007). This suggests that while individual components of a ceiling grid are inherently brittle, (Pourali et al, 2016) for ceilings where some tile loss is acceptable, it is reasonable to assume some level of post elastic performance (up to a ductility of 2.0 with specific design considerations). Shake table testing of suspended ceilings has mostly considered horizontal motions, with limited studies that also include vertical accelerations [Flude et al, 2022]. Recent studies on the seismic performance of suspended grid and tile ceilings show that the vertical component of earthquake shaking may have a significant effect on the behaviour of grid and tile ceilings [Ryan, 2022]. As the ceiling tiles are critical in maintaining the in-plane rigidity of the suspended ceiling system, the loss of too many ceiling tiles can lead to premature failure of the ceiling grid and complete collapse of the entire suspended ceiling system.

Research undertaken at the University of Nevada Reno [Ryan, 2022] showed an extraordinary response of suspended grid and tile ceilings systems. Of importance, the testing highlighted the difference between the amplifications of vertical accelerations in areas adjacent to columns compared to the middle of floor slabs as a result of the spectral content reflecting the flexibility of the floor system. The impact of the increased vertical accelerations on the suspended ceilings was significant and whilst additional testing is required to better understand the response, the implications of vertical accelerations on the performance of suspended ceilings will not in future be allowed to be ignored.

Grid and tile suspended ceiling manufacturers offer ceiling clips that are intended to keep ceiling tiles in place when subjected to upward wind and earthquake loads, however the inclusion of ceiling clips can introduce challenges for construction and maintenance as ceiling clips are installed sequentially and will likely require removal and replacement of a significant amount of the ceiling to enable full replacement of the clips.

Greater understanding of the response of grid and tile suspended ceiling systems that have, and don't have, back braces, that are influenced by both horizontal and vertical accelerations and the impact of including ceiling clips is needed for designers both here and internationally so that we can better inform designers of these systems.

Response of plasterboard suspended ceilings

The behaviour of plasterboard suspended ceilings is much simpler than grid and tile suspended ceilings due to their regular fixings to the support framing and their ability to behave as a relatively rigid diaphragm when subjected to lateral inertia loads. For moderate to large size plasterboard ceilings, it is expected that any members or connections that might be overloaded should be able to redistribute forces to adjacent elements in the overall system. These inherent redundancies in suspended ceiling plasterboard system make well designed braced ceilings less vulnerable to the effects of vertical and horizontal accelerations.

Typical framing types of suspended ceilings

The two typical suspended ceiling types used in NZ are exposed grid and tile and plasterboard lined concealed.

Exposed grid and tile ceilings are typically built using proprietary cold form main tees and cross tees at spacings of 1.2m to 0.6m. A ceiling tile is then placed on the ledges created by the tee sections and mostly held in place by gravity alone. These ceilings are favoured by architects and building owners in areas where access into the ceiling plenum in the future might be required.

Plasterboard lined concealed ceilings are typically built using proprietary cold form top cross rails at 0.9-1.2m spacing and furring channels at 0.4-0.6m. Plasterboard linings are fixed to the furring channels creating a positive connection to the supporting grid. These ceilings are favoured by architects and building owners in bathrooms and typically areas not likely to require access in the future.

Typical suspended ceiling seismic restraint strategies

The two typical strategies for restraining ceilings are by tying ceilings to partition walls or connecting via back braces to the structure above. When connecting to partition walls, designers are advised to fix to one partition wall and float on the opposite side for smaller rooms refer Figure 2 below. For medium sized rooms where the connection to the partition wall would exceed its capacity, designers can opt for a seismic gap within the ceiling which enables fixing to opposite walls refer Figure 2 below.

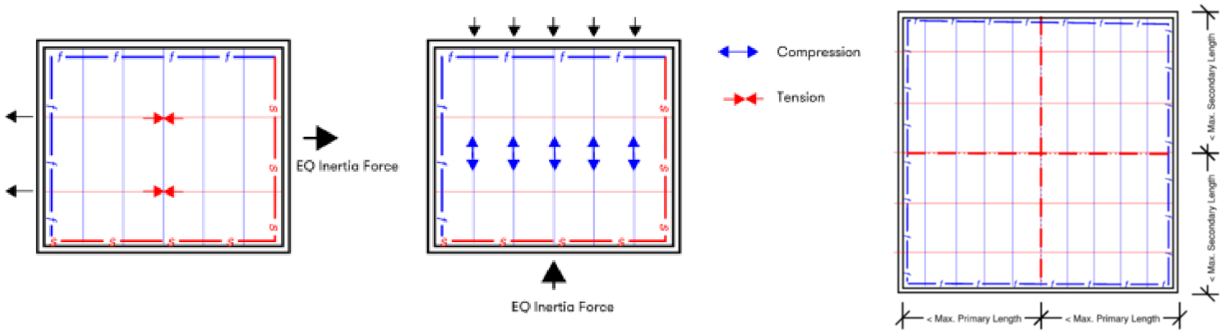

Figure 2. Plan view of small rooms with fixed (f) and floating (s) edge connections (left), medium sized room fixed to walls with central seismic gap (right)

When seismically restraining suspended ceilings to the structure above the designer should isolate the ceiling around the edges to avoid incompatible movement between the structure above and the partition walls around the perimeter, refer Figure 3. For this fully floating suspended ceiling, designers then need to locate back braces to avoid overloading a) ceiling grid structural elements or splices/connections between elements, b) back brace to ceiling grid connection or c) the back brace. Often with grid and tile ceilings it is the splice connections between main tees or cross tee connections to the main tee that govern the placement of back braces due to their low load carrying capacity. A hybrid approach, utilising lines of restraint above the ceiling (bulkheads) and seismic joints where necessary can also be a useful option, particularly for large ceilings. One of the main benefits to this is that it does not rely on the diaphragm strength of the ceiling to transfer load to the supporting structure resulting in a more robust and definable load path for larger ceilings.

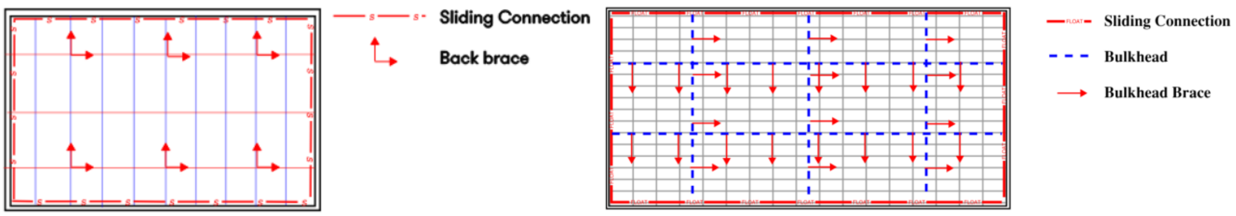

Figure 3. Plan view of back braced suspended ceiling with perimeter floating/sliding connection

Load accumulation adjacent to restraint

It is expected that grid members can deliver axial forces into back braces through both tension and compression as outlined in Figure 4 below. These accumulate and are usually at their maximum immediately adjacent to the back brace connection. Designers need to consider that grid and tile ceilings often specified by the architect, come in light and heavy-duty classifications. If a light duty ceiling is specified, the grid members have low tension or compression capacity (depending on the supplier it can be around 0.4kN) through the grid to the back brace which severely limits the tributary area which can be supported by a back brace when you consider some proprietary back brace systems have capacity for up to 2.4kN.

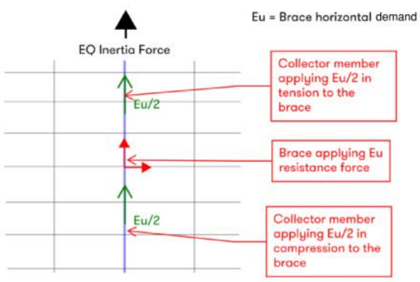

Figure 4. Plan view example of suspended ceiling load accumulation adjacent to back brace

Performance of ceilings with ceiling clips

AS/NZS 2785:2020 recommends tile hold down clips are provided unless designed otherwise. Based on research and observed failures the authors agree with AS/NZS 2875 that installing ceiling clips likely improves seismic resilience. We recommend specification of hold down clips, however, this may not be appropriate for all projects and areas in a building. Access, maintenance and functionality should all be considered as designing on that basis that clips are installed could result in under designed seismic restraints if they are removed at a later date. Testing (Flude 2022, Ryan 2022, Badillo-Almaraz 2007) has shown that ceiling and tile systems fail rapidly once more than sporadic ceiling tile loss occurs.

If the ceiling design is undertaken on the basis that ceiling clips are to be installed it is important that if the any ceiling tiles are removed during the life of the ceiling that the ceiling clips are reinstalled. The potential implications for maintenance should ideally be discussed and agreed with the building owner/facilities manager if clips are to be specified. Signage may be required to ensure that maintenance contractors and facilities managers are aware of provision of the clips and the need to reinstall if any tile is removed.

If ceiling clips are to be included as an integral part of the design to achieve the required seismic performance, the designer must first assess the risk of the ceiling clips being removed during the life of the ceiling. Ceilings in buildings that have high maintenance requirements (e.g. hospitals) have a high chance that ceiling tiles will be removed to undertake maintenance and the clips not replaced. For these types of buildings, or zones of buildings, designers should, design the ceiling to achieve the required seismic performance without ceiling clips, whether or not clips are actually specified.

Technical Information from ceiling system suppliers

Experience from the authors of this paper is that designers have often been unable to obtain detailed technical information from suppliers without signing non-disclosure agreements (NDA). It is our experience that consultants are unwilling to take on the liability of signing the NDA agreements and therefore there is a lack of needed technical transparency for the designer.

We therefore recommend that Engineers include requirements for the supplier information to be provided along with the testing evidence as part of the specification, refer to Section 4 of this paper for further information.

4 RECOMMENDED SPECIFICATION APPROACHES

The project procurement strategy needs to align with the design and documentation for non-structural elements and this is of particular importance for ceiling design that interfaces with structure, architecture and building services.

Ceiling design and documentation can progress in various ways. There are three typical procurement strategies for ceiling design and documentation. The implications of each procurement strategy on the ceiling design and documentation, including specification requirements are discussed in the sections below.

Traditional Procurement (design followed by tender – ceiling design developed sufficiently to provide PS1 for Building Consent)

In this scenario the architect will specify a particular ceiling system and the seismic engineer will complete the seismic design of the ceiling in accordance with one of the methods described in Section 3 of this paper. It is noted that the ceiling design may include connection to, and seismic restraint of, the ceiling via connection to partition walls. The seismic engineer will coordinate the seismic restraint design with other disciplines as appropriate (e.g. building services engineers, fire engineer and architect).

Following tender the seismic design of the ceiling and the interrelated partition design (where connection and restraint via the partition has been assumed) may need to be updated or completed when the actual partition and ceiling suppliers and their designers are engaged by the main Contractor. At completion of the detailed design phase the seismic engineer's deliverable should consist of:

Table 1: Deliverables at detailed design.

Item	Deliverable	Description
1	Drawings	A reference ceiling seismic design which identifies a ceiling brace layout, assumed ceiling capacity, and assumed length(s) of ceilings which can be perimeter fixed.
2	Report	Non-structural seismic restraint strategy
3	Specification (with these clauses incl.)	• Specify capacity that the ceiling system is to achieve. For example, main tee splice connection capacity to exceed 120kg (actual capacity dependent upon system being specified). • Specify requirements for the partition walls, eg. Partition walls to have capacity to resist XXkN/m (advise the ULS and SLS load) seismic load from ceiling. Ensure this requirement is included in the Partition Wall specification as well. • Specify the testing requirements of the ceiling system (e.g. in accordance with AS-NZS 2785:2020). Require evidence of the testing and results of the testing to be provided to the seismic restraint engineer. • Where the system is broken down into sub-assemblies, each sub-assembly shall be tested individually, and testing and capacity of sub-assembly provided to the seismic restraint engineer. • Specify requirements for coordination of the actual procured ceiling system including the seismic restraints with building services, partitions, structure.
4	PS1	Producer Statement for the design of the suspended ceilings and if the partitions are included in the load path the PS1 to include the design of the partitions.

As the ceiling design is often undertaken prior to the ceiling supplier being engaged, there is a risk that redesign is needed which can result in conflict with other building components, there is also a risk that the proposed ceiling system component capacities do not meet the design. The responsibility for resolving these conflicts and ensuring the system achieves the required capacity should be included in the Specification and highlighted in the tender documentation.

Early Contractor Involvement

When Early Contractor Involvement (ECI) occurs during the design phase, the seismic design of the ceiling system to be used, and any partition walls where they are used as part of the seismic restraint of the ceiling system will include input from the contractor and subcontractor. Specific products will be chosen and included in the design and technical specification with the expectation that there is lower risk that significant changes to the ceiling system will be required during the Construction phase and therefore reduce potential redesign and potential conflicts with other components.

The seismic restraint engineer's deliverables for this procurement strategy would be the same as for Traditional Procurement in the previous section.

Design and Build

For a Design-Build strategy the seismic engineer will work with the Main Contractor and the ceiling and partition subcontractor to complete the design and coordination of the suspended ceiling design. The seismic engineer would request confirmation that the proposed ceiling system has been tested as required by AS/NZS 2785 and review the test results during the design phase.

5 RECOMMENDED DESIGN PRACTICE AND FUTURE RESEARCH

We recommend that practicing professional seismic engineers use the following design practice for the seismic design of suspended ceiling:

1. Choose the suspended ceiling seismic design method(s) that best fits the project, as described in Section 3 of this paper.
2. Prepare a non-structural seismic restraint strategy document. This document should clearly describe what design method is being used to seismically restrain the ceiling and the assumptions their design is based upon.
3. Drawings should clearly show which ceilings are being retrained to walls and which are braced to the structure above. If restrained by partition walls, the designer should communicate the load demand to those walls so that the partition wall designer takes that load into account in their design.
4. As grid system capacities vary, we recommend the designer clearly document the grid capacity they are relying on and request testing data from the proprietary system providers which align with AS/NZS2785's requirements. As noted in Section 2 of this paper, it is important that the seismic design engineer checks that test data provided by manufacturer's aligns with the testing setup, e.g. system test results to ASTM E580 are not fully applicable for fully floating ceiling systems, but individual component/connections testing could be if result can translate to ASNZS2785.
5. Assist in coordination of the suspended ceiling seismic restraints with building services, passive fire components, architectural and structural components to identify and address significant clashes as a project team during design phase and resolve clashes to an acceptable level during construction phase (noting that responsibility for coordination during the design phase may be a different entity to the entity responsible for coordination during the construction phase).

Prepare a technical specification that states the required capacity of the ceiling system and sub-assemblies, and requirements for the manufacturer to provide evidence of testing to verify the ceiling system meets the capacity requirements.

Future research into the effects of both horizontal and vertical accelerations on grid and tile fully floating ceilings with different seismic restraint solutions e.g. back bracing at different setouts, diagonal wire restraints, systems with ceiling clips and systems without ceiling clips. This research will support the understanding of the seismic performance of suspended ceilings and will guide future design practice.

As seismic ceiling clips are difficult to reinstall following maintenance access into the ceiling cavity, we would like to see proprietary manufacturers develop systems that can restrain tiles vertically but are able to be released from below the ceiling for access into the ceiling cavity and easily reinstalled following the maintenance works.

References

American Society for Testing and Materials International (2011). *"E580/E580M-11b 2011.Standard Practice for Installation of Ceiling Suspension Systems for Acoustical Tile and Lay-in Panels in Areas Subject to Earthquake Ground Motions"*. PA, USA.

Australian/New Zealand Standard (2020). "AS/NZS2785: Suspended ceilings – Design and installation". Standards New Zealand, Wellington, 85 pp. http://www.standards.govt.nz/shop/https://www.standards.govt.nz/shop/ asnzs-27852020/

Badillo-Almaraz H, Whittaker AS, Reinhorn AM (2007). "Seismic fragility testing of suspended ceiling systems". *Earthquake Spectra*, **23**(1): 21-40.

Dhakal RP, MacRae GA and Hogg K (2011). "Performance of Ceilings in the February 2011 Christchurch Earthquake". *Bulletin of the New Zealand Society for Earthquake Engineering*, 44(4): 379-389.

Dhakal RP, MacRae GA, Pourali A and Paganotti G, (2016). "Seismic Fragility of Suspended Ceiling Systems Used in NZ Based on Component Tests". *Bulletin of the New Zealand Society for Earthquake Engineering*, Special Issue on Seismic Performance of Non-Structural Elements (SPONSE), **49**(1): 45-63. https://doi.org/10.5459/bnzsee.49.1.45-63

Flude CCW, Davidson GA, Lau DT, Erochko J, Kasai K (2022) "Seismic Performance of Suspended Ceilings and Development of Floor Motion Responses for Experimental Testing". *Fifth International Workshop on the Seismic Performance of Non-Structural Elements (SPONSE/ATC-161)*, 5-7 December 2022, San Francisco, USA, pp. 171-181.

Glogau, O. & Clark, W. 1979. "Suspended Ceiling Systems – The Seismic Hazard and Damage Problem and some Practical Solutions", *South Pacific Regional Conference on Earthquake Engineering*, May 1979.

Guzman Pujols JC, Ryan KL (2020). "Slab vibration and horizontal-vertical coupling in the seismic response of low-ris irregular base-isolated and conventional buildings". *Journal Earthquake Engineering*, **24**(1), 1-36. https://doi.org/10.1080/13632469.2017.1387197

Long J, Baird A, Pourali A, Kam W.Y (2023). "Seismic design of suspended lightweight ceilings – what's the ductility?". *Proceedings of New Zealand Society of Earthquake Engineering (NZSEE) Conference,* Auckland, NZ, 19-21 April 2023, Paper No 143.

Pourali A, Dhakal RP and MacRae GA (2014) "Seismic Performance of suspended ceilings: Critical review of current design practice". *Proceedings of New Zealand Society of Earthquake Engineering (NZSEE) Conference,* 21-23 March 2014, Auckland, New Zealand, Paper No 68, 8pp.

Rihal SS and Granneman G (1984). *"Experimental Investigation of the Dynamic Behavior of Building Partitions and Suspended Ceilings during Earthquakes"*. Report No. ARCE R-84-1, California Polytechnic State University, San Luis Obispo, California, USA.

Ryan KL (2022) "Influence of Vertical Floor Accelerations on the Seismic Performance of Buildng Non-Structural Elements". *Fifth International Workshop on the Seismic Performance of Non-Structural Elements (SPONSE/ATC-161)*, 5-7 December 2022, San Francisco, USA, pp. 46-56.

Standards New Zealand (2016). "*NZS1170.5 Supp 1: Structural Design Actions. Part 5: Earthquake Actions – New Zealand*". Standards New Zealand, Wellington, 76 pp. http://www.standards.govt.nz