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Seismic design of suspended lightweight ceilings – what's the ductility?

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ABSTRACT

The design of suspended ceilings has gone through significant change and the level of compliance required has increased substantially in the last few years. This was largely due to the generally poor performance of these systems in the Christchurch and Kaikōura earthquakes and the subsequent requirement for ceiling seismic design by territorial authorities around the country. It is now more common for the design to occur at the consent stage where previously there may not have been a seismic design at all. Along with this, changes to the seismic loading code, NZS1170.5:2004 A1 (2016), the suspended ceiling design code, AS/NZS 2785:2020 and NZS3101:2006-A3(2017) have increased the ceiling seismic loading, testing and performance requirements. This paper first reviews the current status of ceiling seismic design and highlights some of the challenges faced by the industry. The paper then presents an approach in harmonising the seismic performance requirements in New Zealand Building Code (NZBC) and the relevant standards (NZS1170.5, AS/NZS 2785 and NZS 3101). We believe a holistic risk-based approach is necessary to avoid impractically onerous ceiling seismic design while maintaining compliance to the performance requirements of the NZBC.

1 BACKGROUND

Suspended ceilings are a common non-structural element installed in buildings across New Zealand and around the world. They are typically used to cover up suspended services, support lights or form part of the acoustic or fire performance of the building. Generally, they can be classified into two main types:

- Exposed grid ceilings (EGC) – suspended support structure visible (e.g. tile and grid ceilings)
- Concealed grid ceilings (CGC) – suspended support structure hidden (e.g. plasterboard lined ceilings)

It has been well reported that CGC's performed significantly better than EGC's in many of the most recent earthquakes including the Canterbury Earthquake in 2011 and Kaikōura Earthquake in 2016 (Dhakal 2011, Baird 2017). While these earthquakes put them back in the focus, problems related to seismic performance of EGC's was a known issue and identified in New Zealand as early as the 1970's (Glogau 1979).

Evidence suggests that this is in part due to the way the ceiling linings or tiles are secured to the grid and the redundancy in the load path (Gilani 2017). In the case of CGC's, the linings are typically nailed or screwed to the underside of the grid which creates a diaphragm to assist with load re-distribution.

In the case of EGC's, the tiles sit on top of the ceiling grid members, but they are typically not positively fixed to the main or cross tees. Some manufacturers recommend the installation of tile hold-down clips, particularly when uplift is a concern. However, this practice is not often followed as it adds cost and reduces access to the ceiling space. While the tiles do assist with overall ceiling system performance because they are not directly fixed they only act in compression. Due to this, the diaphragm of an EGC is much more flexible and significantly larger movement occurs under seismic accelerations than in a CGC. Figure 1 below shows general construction methods of the two types of ceiling systems.

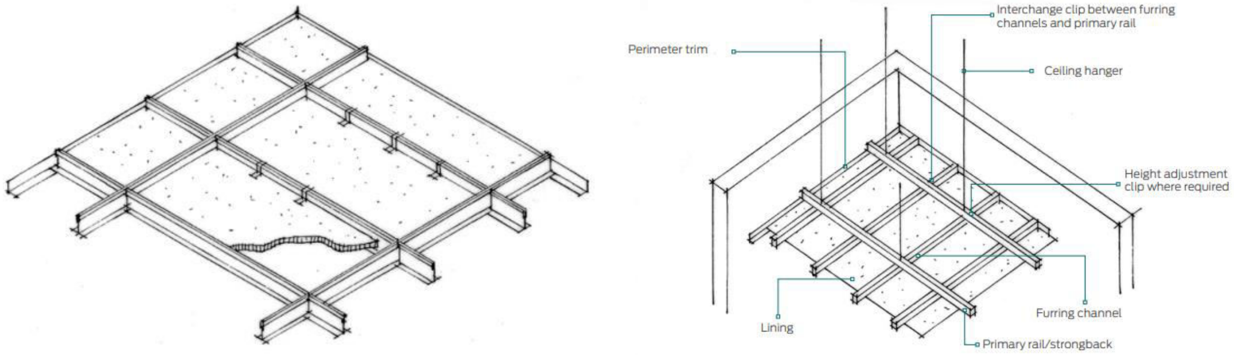

Figure 1 - Schematic of an EGC and a CGC (Berry 2015)

In a seismic event, suspended ceilings can be subjected to significant horizontal and vertical accelerations, along with additional displacement-based loads. Careful detailing is required, particularly at tee terminations, to ensure that there is sufficient strength to carry seismic loads but also enough allowance for seismic movement to reduce the effects of relative drift. Two of the most common methods of restraining ceilings, perimeter restrained and back-braced are outlined below.

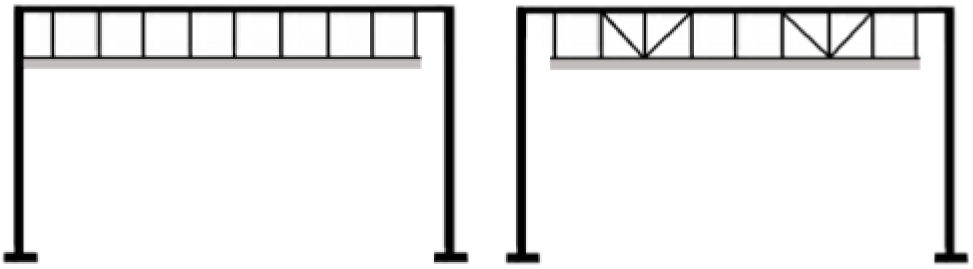

Figure 2 - Schematics of perimeter restrained and back-braced ceilings (Berry 2015)

Perimeter restrained ceilings are laterally restrained by anchoring two orthogonal edges of the ceiling to the surrounding wall or structural element. The opposite edges are allowed to slide (or float). This approach avoids the ceiling being loaded by opposing movement of the partition walls.

Back-braced ceilings are braced to the structure above using either wires or cold-form steel studs. They are not connected to the perimeter wall or frame, with the gap between the ceiling and the surrounding wall needing to be able to accommodate relative inter-storey deflections.

2 CHALLENGES FACED

While the above approaches are reasonably clearly documented in industry design guides such as the AWCI ceiling code of practice and other proprietary ceiling guides (T&R, 2017 & Armstrong, 2019), these are often overly simplistic and do not clearly define load paths or detail what to do with a non-regular grid. For example, back-braced ceiling design often assumes a nominal brace capacity, however, the ability of the grid members to transfer these loads to the brace may not be considered. Similarly, there is often insufficient data on the ability of grid members to transfer these loads, or act as a diaphragm.

2.1 Design Inconsistencies

In the aftermath of the Christchurch earthquakes there were several significant revisions to two relevant standards applicable to the design of suspended ceilings

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

They include updates to design loads and allowable ductility, acceptable methods of testing and stricter anchoring requirements. However, most of these updates have not been directly incorporated into the NZBC and many major design inputs and decisions remain poorly defined following the revisions. Consequently, ceiling design still requires engineers to use engineering judgement, find alternative solutions, or apply first principles as reasonable grounds for their designs.

This lack of clarity has led to significant inconsistency and variability in the ceiling design approach used around New Zealand, particularly in irregular shaped areas such as long corridors and larger braced ceilings. Two commonly observed design inconsistencies that have significant implications are described below:

- Performance objectives and applicable limit states used for ceiling design: This impacts whether ceilings are designed for Serviceability Limit State (SLS1, SLS2) and/or Ultimate Limit State (ULS).
- Ceiling ductility used for ULS ceiling design. Updated requirements in AS/NZS 2785 (2020) state that all ceilings in New Zealand should be designed to elastic seismic actions.

2.2 Part categories and applicable limit states

Part categories and applicable design limit states for suspended ceilings are covered by NZS 1170.5 Section 8 which is directly referenced by the NZBC. The current revision of the standard includes amendment 1 (2016), however, the building code has not yet been updated to include this version of the standard and thus it does not form part of the minimum code requirements.

The amendment incorporates several updates relevant to the design of suspended ceilings. Specifically, additional requirements have been added for non-structural elements in importance level 2 and 3 buildings. Critical elements should now be classified as part category P.5 meaning that they need to be SLS2 performance criteria. Additionally, clarifications have been added that describe when ULS performance requirements needed to be considered, refer Table 1:

Table 1 - Summary of potential applicable design limit states for different building importance levels

Standard	**IL2 & IL3**	**IL4**
NZS 1170.5:2004 (excl. Amd 1)	ULS* & SLS1	ULS*, SLS1 & SLS2
NZS 1170.5:2004 (inc. Amd 1)	ULS**, SLS1 & SLS2	ULS**, SLS1 & SLS2

*Only applies to parts that weigh more than 10 kg and can fall more than 3.0m onto an accessible area.
**Parts that weigh less than 7.5kg, that can fall less than 3.0m need not be considered for ULS.

The threshold for parts that are considered a life safety risk has dropped from 10kg to 7.5kg and the definition of a "part" was also clarified in the amendment. Under the original interpretation, provided each individual element of a ceiling (e.g. each tile or cross tee) weighed less than 10kg, the part was not considered to pose a life safety risk and did not need to meet ULS performance objectives. Under the new interpretation, if the ceiling system as a whole or elements of the system weighed less than 7.5kg and could fall less than 3.0m it did not need to meet ULS performance criteria. This is a significant change as it essentially means that any ceiling of a reasonable size, needs to be designed to ULS loads where previously, SLS1 design loads were considered acceptable.

2.3 Performance Objectives

Directly related to the applicable limit states above, the required performance objectives are also inconsistent between standards (See Table 2).

Table 2 - Summary of performance requirements for serviceability and ultimate limit state

Standard	**SLS1**	**SLS2**	**ULS**
NZS 1170.5:2004	Essentially no damage	Return to operable state within an acceptable timeframe	Avoidance of collapse or loss of support**
AS/NZS 2785:2020	Essentially no damage*	Loss of serviceability acceptably low, maintains performance	Avoidance of rupture, instability, or loss of equilibrium

* For some systems, "no damage" at serviceability limit state is not possible (e.g. square set corners).
** Amendment 1 of NZS1170.5 allows the use of tethers to meet life safety ULS requirements for some parts and components

The objectives described in AS/NZS 2785 are generally more prescriptive but overall, much more restrictive, especially at the ultimate limit state.

2.3.1 Serviceability Limit States

While the performance objectives above are reasonably clear, designing a ceiling system in a way that achieves the required performance is much more difficult. This is particularly problematic at SLS1 where essentially no damage is required. Even at small seismic loads and drift, damage has been observed at ceiling edges and tiles are likely to fall out. In addition to this, gaps required for seismic movement typically have an adverse effect on fire and acoustic rating which leaves designers without a clear way to meet this criterion while still conforming with seismic requirements.

At SLS2 while there are still issues determining what good performance looks like, the criteria are reasonably clear and consistent between standards essentially requiring the ceiling system to be easily repaired or remain operable.

2.3.2 Ultimate Limit State

ULS performance objectives were modified in amendment 1 to NZS 1170.5, adding tethering provisions which exempts some parts from needing to comply with ULS design loads. This essentially absolves the engineer from responsibility of this aspect of the design, particularly if a specific gravity design has not been carried out. Relying solely on tethering to meet ULS performance requirements may be appropriate for certain non-structural elements, but evidence suggests that this approach may not be appropriate for suspended ceilings. Shake table testing results in several studies found that large scale grid failure combined with major loss of tiles can result in large scale ceiling failure which is a significant life safety hazard (FEMA P-58-1. 2012).

Conversely, AS/NZS 2785:2020 has much more restrictive performance criteria, stating that the system must not rupture, become unstable or lose equilibrium at the ultimate limit state. This again is inconsistent with shake table testing that showed that the grid remained largely intact even with isolated grid failures and up to 30% of tiles displaced.

2.4 Ductility and Component Response

Ductility is the measure of an object's ability to deform or deflect plastically without failure. In the context of parts and components it reflects its post-elastic load carrying capacity. This is particularly important with a complex non-linear system such as a suspended ceiling. While individual elements (such as grid or wall connections) may act in a brittle manner when loads are directly applied, the system does not necessarily respond the same way. Tile movement, along with grid flexibility all contribute to the overall ductility of a suspended ceiling system. Load can also be redistributed to adjacent tees when a grid failure occurs which adds to the overall resilience of the system.

Assessing the actual response of the system and associated design acceleration can be very difficult without robust testing data that is expensive to obtain. This is because not only does the response of the system need to be considered but also that of the supporting structure. As a result, most standards and guidance simplify these effects for parts and components down to a few factors which are then used to scale peak ground accelerations (PGA). The approach used in NZS 1170.5 is outlined below:

$$F_{ph} = C_p(T_p) \cdot C_{ph} \cdot R_p \cdot W_p \tag{1}$$

where the horizontal design earthquake action F_{ph} is a function of $C_p(T_p)$ the horizontal design coefficient (based on site hazard coefficient for T=0 and part period less than 0.75s), C_{ph} the part component response factor, Rp the part risk factor and W_p the seismic weight of the part. These factors are reasonably well defined throughout NZS 1170.5 except for the part response factor.

As mentioned above, AS/NZS 2785:2020 includes updated recommendations for allowable ductility for suspended ceilings, advising that elastic seismic loads should be used (μ=1.0). This is in direct conflict with NZS 1170.5 which advises a part ductility of 2 or 3 may be assumed for ULS design of EGCs and CGCs, respectively. This change has a significant impact on the design loads for suspended ceilings, increasing demands by 180-220%. While a low level of component ductility may be appropriate for suspended ceilings, defining the overall response using this one metric does not take into consideration other significant factors relevant to suspended ceilings.

3 INTERNATIONAL DESIGN APPROACHES

In contrast to the New Zealand design approaches described above; the North America standards tend to be much more prescriptive in design. There has also been significant shake table testing carried out on suspended ceilings all of which provides insight into the seismic performance of ceilings, their components and the hierarchy of damage expected.

3.1 ASCE 7-16

A good example of this is in the American loading standard ASCE 7-16. Section 13 covers the design of non-structural elements with clause 13.5.6 providing additional specific requirements for suspended ceilings. There are several aspects which are relevant to this paper which have been summarised below:

- Requirement exemptions for ceilings below a certain size (13.4m²)
- Minimum design horizontal accelerations
- Installation requirements for seismic regions A to F (ASTM C636, C635 and E580)
- Maximum sizes for unbraced ceilings (92.9m²)
- Additional requirements for large ceilings (>232m²)
- Minimum tension/compression load capacity requirement for hangers, grids members and connections.

Along with this, the methods of determining design seismic loads on parts and components varies significantly to those presented in the New Zealand standards above. One such difference is the way design spectral response curves are produced. NZS 1170.5 takes the site hazard coefficient for T=0s and factors it up based on the expected period of the part while ASCE 7-16 takes the design spectral response at short period accelerations and factors it down. For reference, the calculation for horizontal design earthquake actions from ASCE 7-16 is shown below (section 2.4 above shows the NZs 1170.5 equivalent):

$$F_P = \frac{0.4 a_p S_{DS} W_p}{\left(\frac{R_p}{I_p}\right)}\left(1 + 2\frac{z}{h}\right) \qquad (2)$$

For part periods less than 0.75s the results are reasonably consistent assuming the same expected equivalent component response. With the NZS 1170.5 method resulting in unfactored accelerations ~20% greater than ASCE 7-16.

Component response is also treated differently; As described in section 2.4 above, the NZS 1170.5 method relates back only to the expected ductility of the part or component with proposed values for each element type included in the standard commentary. These values are based on the guidance provided in FEMA 356 (refer NZS 1170.5 Commentary). ASCE 7-16 instead uses the same method described in FEMA 356, advising values for the expected component amplification (based on the flexibility of the component's attachments) and component response (based on how the component is expected to respond to seismic accelerations).

It is worth noting that the expected response for ceiling components differs between FEMA 356 and ASCE 7-16, increasing from 1.5 to 2.5. Table 3 below summarises the differences and overall effect on the equivalent horizontal component response for suspended ceilings designed to NZS 1170.5 (with a part ductility factor of 2).

Table 3 – Comparison between equivalent component response factors from different standards

Standard	R_p	C_{ph} (Equivalent)
NZS 1170.5:2004	-	0.55
FEMA 356	1.5	0.67

ASCE 7-16	2.5	0.4

3.2 FEMA P-58

While ASCE 7-16 covers the International Building Code (IBC) compliance requirements and gives good guidance and solutions for determining design loads for force-based assessments (for seismic hazard zones A to F), it does not include information on specific performance requirements for serviceability of suspended ceilings. This is particularly important in regions such as California where Health Care Access and Information regulations apply (HCAI, previously OSHPD) and other countries with high seismic risk such as New Zealand. Alternative methods of determining the overall building performance and non-structural elements within it have instead been developed. One such method which contains significant data on suspended ceilings is FEMA P-58.

The document provides parameters which can be used to generate fragility curves that are component specific and cover three different damage states. The performance indicators and damage state definitions are outlined below:

- Damage State 1 (DS1): up to 5% tile dislodgement, no damage to in-lain services and sprinkler pipes, no life safety consequence or injury. Consequence: reinstall tiles, clean up (hours of downtime),
- Damage State 2 (DS2): up to 30% tile dislodgement, damage to grids. Consequence: reinstall tiles and damaged grids, clean up (days of downtime), minor injury risk. Repair and downtime cost up to 50% of value.
- Damage State 3 (DS3): Major Ceiling Damage and some grid collapse (~50% grid collapse), Consequence: total replacement of grid and tile, minor injury risk if heavy items are separately tethered.

Along with the benefit of quantifying the expected damage, fragility curves can also be used to communicate the expected risk of a particular damage state occurring to clients.

4 A HOLISTIC APPROACH

Our proposed approach combines several of the elements discussed above and is based on compliance with the NZBC to meet life-safety performance criteria, taking into consideration the relative risk posed by suspended ceilings. Aspects of various standards and guidance above have been applied using a holistic risk-based approach to meet (or in some cases exceed where appropriate) minimum serviceability limit state requirements of the code. Alternative performance levels for ceilings where additional damage control limit states (DCLS) may be relevant have also been proposed.

The approach follows the general procedure below:

1. Determine ceiling classifications for each ceiling type – life safety risk posed and level of redundancy,
2. Determine the horizontal design coefficient applicable to the ceiling (based on building properties and location)
3. Define the performance requirements (enhanced continuity, DCLS where relevant) – serviceability limit state requirements,
4. Define design component response based on the performance required at each limit state
5. Determine maximum unbraced ceiling lengths based on the design seismic force at each limit state for each ceiling type, assuming a perimeter fixing solution and continuous ceiling diaphragm action.

6. Where maximum lengths are exceeded, consider seismically separating the ceiling or laterally bracing to the soffit.

4.1 Ceiling Classifications

The classifications below are used to quantify the life-safety hazard and risk associated with a ceiling in an earthquake. They have been broadly based on definitions provided in the seismic assessment guidelines for existing buildings (Seismic Assessment of Existing Buildings, 2017). They are classified based on the hazard associated with the ceiling (its weight and height above ground) but also the risk posed when a failure occurs (e.g. available shelter). Three primary classifications have been defined:

C01 – Ceiling as a whole and, individual ceiling components represent a hazard to life within the structure.

C02 – Ceiling as a whole but not individual components represents a hazard to life within the structure.

C03 – Ceiling as a whole and individual ceiling components do not represent a hazard to life within the structure.

C01 and C02 are only subtly different but essentially define what level of grid damage and fallen tiles is acceptable at the ultimate limit. For ceilings classified as C02, moderate damage to the ceiling grid and fallen tiles are acceptable as on their own they do not pose a life safety risk, but large-scale collapse should be avoided. Conversely, for classification C01, even minor damage could pose a significant life safety risk.

Consideration should be given to the level of redundant vertical support available when classifying ceilings. Heavy suspended elements should be adequately supported (tethered) to reduce the life safety risk they pose in an earthquake. This design methodology is clarified in the tethering provisions of amendment 1 of NZS 1170.5 and is consistent with evidence from the Christchurch and Kaikoura Earthquakes. Even though sections of the ceiling did collapse, no deaths directly resulted from suspended ceiling failures and heavier elements that were adequately secured to the soffit remained supported (MacRae et al. 2011).

While tethering reduces the life safety risk posed by a suspended element, it does not necessarily remove the need for a designer to consider ULS demands. Large-scale damage and collapse still needs to be avoided as this can result in cascade failure of overloaded vertical supports.

Figure 3 - Extensive damage to suspended ceilings in the Christchurch Earthquakes (MacRae et al. 2011)

4.2 Performance Requirements

Alongside the life safety risks posed, performance requirements also need to be considered. These requirements define the level of damage that is acceptable at each limit state. While part categories are stated in section 8 of NZS1170.5, acceptable damage limits have not been defined. Using our approach, damage states as per FEMA P-58 have been used to quantify acceptable performance for serviceability and ultimate limit states. Table 4 below summarises the proposed damage limit states applicable to ceilings based on the classification proposed in section 4.1 and part categories defined by NZS 1170.5.

Table 4 - Proposed acceptable damage states for ceilings based on part category and classification

Ceiling Classification	P.2	P.3	P.4	P.5	P.7
C01	DS2	DS2	DS2	DS1/DS2*	DS1
C02	DS3	DS3	DS3	DS1/DS2*	DS1
C03**	N/A	N/A	N/A	DS1/DS2*	DS1

*Note that level of damage acceptable for ceilings categorised as P.5 should also take into consideration requirements of other services attached to the ceiling.

**As per amendment 1 of NZS 1170.5, this classification can only be used for ceilings that as a whole weigh less than 7.5kg.

Ceilings classified as C01 or C02 are always categorised as at least P.2 or P.3 as they pose a life safety risk and should be designed to ULS loads but the level of damage acceptable is different.

From a minimum Building Code perspective P.5 only needs to be considered for parts installed in importance level 4 buildings. However, enhanced building continuity should be considered in accordance with NZS 1170.5 amendment 1 as appropriate.

In general, C03 should only be considered for low-risk ceilings where complete collapse is acceptable at the ultimate limit state. As the weight threshold is so low, usually this can only be applied to small ceilings.

4.3 Design Ceiling Accelerations

To translate the damage states (DSs) proposed in Section 4.2 into a quantity applicable to design, ceiling fragility curves are used. These fragility curves are obtained from experimental tests (FEMA P-58) and show the probable peak floor acceleration corresponding to the commencement of damage states DS1-DS3 described in Section 3. Unbraced values from FEMA P-58/BD-3.9.4 for each damage state are compared against NZS 1170.5 design accelerations using ductility factors of 1.25-2 and the same ceiling grid input parameters. A summary of the parameters used is shown Table 5 below:

Table 5 – Ceiling design parameters

Seismic weight	Design grid length	Grid spacing	Grid capacity	Restraint configuration	Brace configuration
7.2kg/m²*	15.2m	600mm	60kg**	Single rivet	Unbraced

*FEMA states the tile weight only, increased design weight to account for grid mass

**Assumed equivalent to the intermediate duty grid used during the FEMA P-58 testing

Using the above parameters and equation (1), equivalent horizontal design coefficients were determined for different component response factors. These have been compared against fragility curves for ceiling type C3032.001c from FEMA P-58/BD-3.9.4 (note the unfactored values have been used as we are not comparing PFA) refer Figure 4 on the following page.

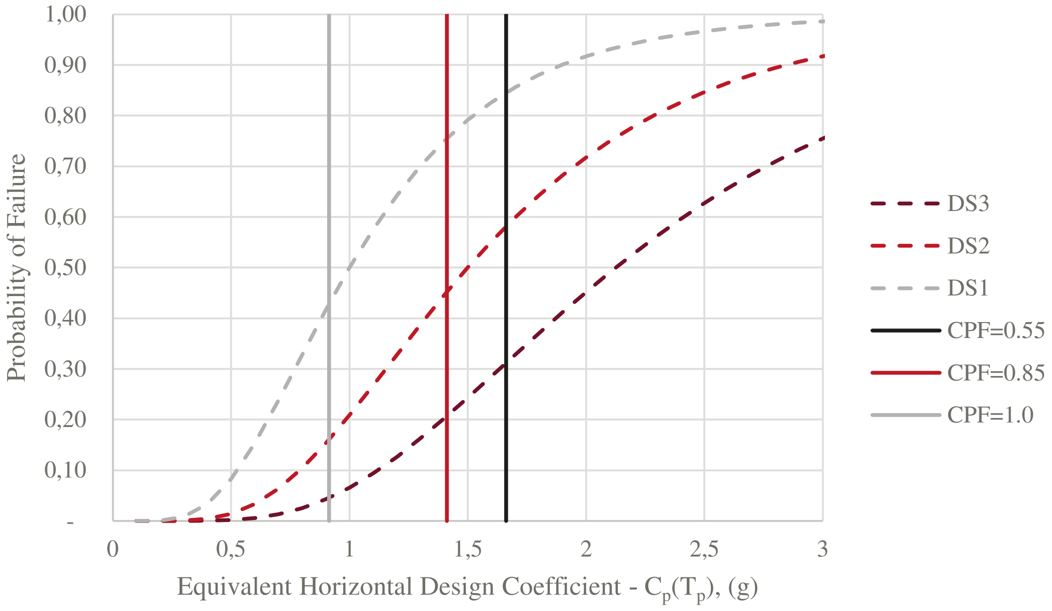

Figure 4 - Comparison between FEMA P-58/BD-3.9.4 fragility curves & NZS 1170.5

A direct comparison between damage states shows that the median grid acceleration for DS1 (effective elastic capacity) is half that of DS3, suggesting that using a component response factor of less than 1.0 is appropriate when designing to DS3 performance criteria at ultimate limit state. The comparison also shows that when a component response factor of 0.55 from NZS 1170.5 is used to design ceilings, the risk of minor damage is high but overall ceiling collapse is relatively low (~30%). Similarly, when designing with a component response factor of 1.0, the risk of grid collapse is very low (<5%) but the risk of grid damage and tile loss is low-medium (<45%).

It is worth noting that failures observed at DS3 typically resulted from pop rivet failure and unseating of grid members along the floating edge (Jenkins, 2015). This suggests that the grid capacity is not the limiting factor and increasing capacity around fixed edges (as is commonly done in NZ) is likely to reduce the probability of grid failure. Studies have also shown that introducing seismic clips at grid connections improves overall grid strength and could reduce the probability of failure of the grid (Pourali, 2016)

4.4 Back Braced Ceilings

The approach above has generally been developed for ceilings installed in an edge restrained configuration. To date, there has been minimal shake table testing carried out on ceilings installed fully floating with rigid back bracing installed. This is mostly because this type of configuration is not permitted for ceilings installed in accordance with ASTM E580 but is common in New Zealand and Australia.

While not directly equivalent, shake table testing has been carried on ceilings installed in accordance with ASTM E580 for seismic regions E and F. An edge restrained configuration is still used but supplementary lateral bracing (with or without a compression post) is also installed at regular centres throughout the ceiling system. While using both restraint methods in the same system introduces a potential relative drift issue, testing has shown that the performance is equivalent or better than using an unbraced configuration (Jenkins, 2015, Jun S. C., 2022).

The testing found that in plane stiffness of the ceiling diaphragm is relatively low, meaning there is often minimal load transfer from unbraced tees to lateral restraints (Jun S. C., 2022). However, it is worth noting that the stiffness and resulting deflection and acceleration along braced lines was significantly lower than those along unbraced lines. The deflection profile in these areas was almost identical to that of the unbraced ceilings (Jun S. C., 2022). This suggests that part of the reason no diaphragm action occurred was that the primary load path was through the fixed edges of the ceiling. This emphasizes the importance of installing floating edges with sufficient clearance on all sides of braced ceilings when diaphragm strength is being utilized.

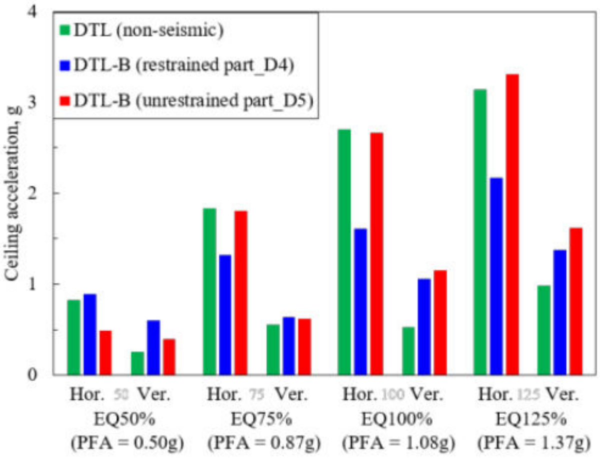

Figure 5 - Comparison between unrestrained, restrained, and non-seismically braced tees (Jun S. C., 2022)

As the performance of back braced ceilings has not been as extensively researched, care should be taken when determining required seismic brace spacing and defining an allowable lateral load that each ceiling brace can support. AS/NZS 2785:2020 provides some guidance on maximum allowable brace spacing (6m x 6m for New Zealand) but care should be taken when applying these limits directly as significant deformation of the grid is likely to occur. In general, lower capacity, more regularly spaced braces are likely to have better performance than higher capacity braces spaced further apart.

4.5 Bulkhead Braced Ceilings

Similar in nature but functionally quite different to back braced ceilings, bulkhead braced ceilings are another commonly specified ceiling bracing design, particularly in New Zealand. Instead of evenly spaced braces throughout the ceiling plenum space, lines of braces are constructed and connected by a continuous bottom track. This track is connected to each tee essentially creating a fixed edge in the plenum space. While there have not been any specific studies done on bulkhead braced ceilings, the design methodology behind them is much the same as edge restrained configuration and overall performance is expected to be similar. However, care needs to be taken when sizing the bottom track. Testing of a braced system with grid reinforcement (similar to a bottom track) found that deflection of the reinforcement should be limited to prevent pounding and unseating along the floating edges of the ceiling (Jun S. C., 2022).

5 SUMMARY AND CONCLUSIONS

Recent changes to relevant ceiling design standards in New Zealand have resulted in significant differences in design methods and construction.

Most significantly, variation in accepted component response along with applicable design limit states and required performance criteria have resulted in design accelerations 180-220%.

Using other interpretations of the code, ULS loads have been met using tethering provisions, essentially absolving the design engineer from this responsibility.

International standards are much more consistent and design information has been backed up with significant shake table testing. The requirements of international codes are typically much more prescriptive and specific installation and testing requirements have been stated.

Damage states and associated fragility functions from FEMA P-58 provide an analytical way to assess the expected damage sustained by a suspended ceilings using a design PFA.

Ceiling classifications based on compliance with the New Zealand Building Code have been used to determine the life safety hazard posed by a ceiling at a given design limit state.

These two concepts have been combined to better define appropriate levels of component response at a given design limit state and quantify the potential residual risk posed.

The examples and analysis used suggest that the damage sustained by ceiling design using a component response of 0.55 (equivalent to $\mu=2$) is significant but the risk of collapse is relatively low (~30%). This is based on a standard ceiling system using a 60kg capacity, strengthening the system will likely reduce the risk of collapse further.

Care should be taken when design fully floating braced ceilings as testing of these type of restraint configurations is not well researched. Adequate clearance should be provided around the perimeter and lower capacity braces spaced more regularly are expected to have better overall performance than higher capacity braces spaced further apart.

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