Seismic design of interior overhead non-structural elements

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ABSTRACT: This paper discusses the seismic design of interior overhead non-structural elements (NSEs) in buildings with reference to current NZ Building Code and Standards requirements and current construction practice.

Recent earthquakes in Canterbury and Wellington have highlighted that losses from damage to overhead NSEs can be significant, and in some cases exceed losses from primary structural damage. Furthermore, the failure of overhead NSEs can become a significant safety hazard to building occupants during an earthquake and inhibit business continuity.

A number of factors have contributed to the poor performance of overhead NSEs. There are limited design standards for overhead NSEs, with different standards for different elements. Moreover, current standards have in some cases proven ineffective in preventing significant damage in recent earthquakes. Furthermore, the design and construction of overhead NSEs is fragmented over a number of different disciplines.

This paper identifies safety and damage avoidance philosophies and proposes changes to current standards. An approach to resolve matters of seismic design of overhead NSEs in a coordinated manner is presented through a case study of a new Christchurch building.

1 INTRODUCTION

Earthquakes in Canterbury and Seddon/Wellington recently have exposed current practice of design and installation of overhead non-structural elements (NSEs) such as suspended ceilings, mechanical and electrical equipment, and fire systems. Each of these elements is distinctly different in structural design and performance. Suspended ceilings in commercial buildings typically consist of a cold formed steel grid in which tiles sit, suspended from the main structure, and may be connected to internal partitions (Fig. 1a). There is a range of ceiling tile weights, from light acoustic tiles weighing 1.5kg/m^2 to heavy mineral fibre tiles weighing in excess of 10kg/m^2. The tiles are sometimes clipped to the ceiling grid but are otherwise sitting freely. Seismic bracing is provided by one of two methods, either fixing along two of the perimeter walls or bracing back to the structure above with a floating perimeter (Fig. 1b). Some older installations are simply secured to internal and external walls with little consideration of seismic separation. In some cases, partitions below ceilings are also braced through the ceiling to the structure above.

Mechanical services, typically consisting of Heating Ventilation and Air Conditioning (HVAC) equipment are either suspended from steel rods fixed to the structure above, or smaller units are supported by the ceiling grid. Some units can be of considerable weight and are required by Standards to be provided with independent seismic restraint. Typical bracing consists of steel tension wires acting diagonally in the corners of the unit, as shown in Figure 1c.

Construction of overhead systems can be complex due to the extent of vertical and bracing support needed for multiple elements. The challenges are further compounded due to different sub-contractors being used for both the design and installation of each element. Subcontractors will typically develop a design and build tender bid without the opportunity to coordinate the design with other overhead

NSE’s. The outcome can often be a clash of structural support resulting in compromise or omission of structural elements, and lack of a coordinated consistent seismic design.

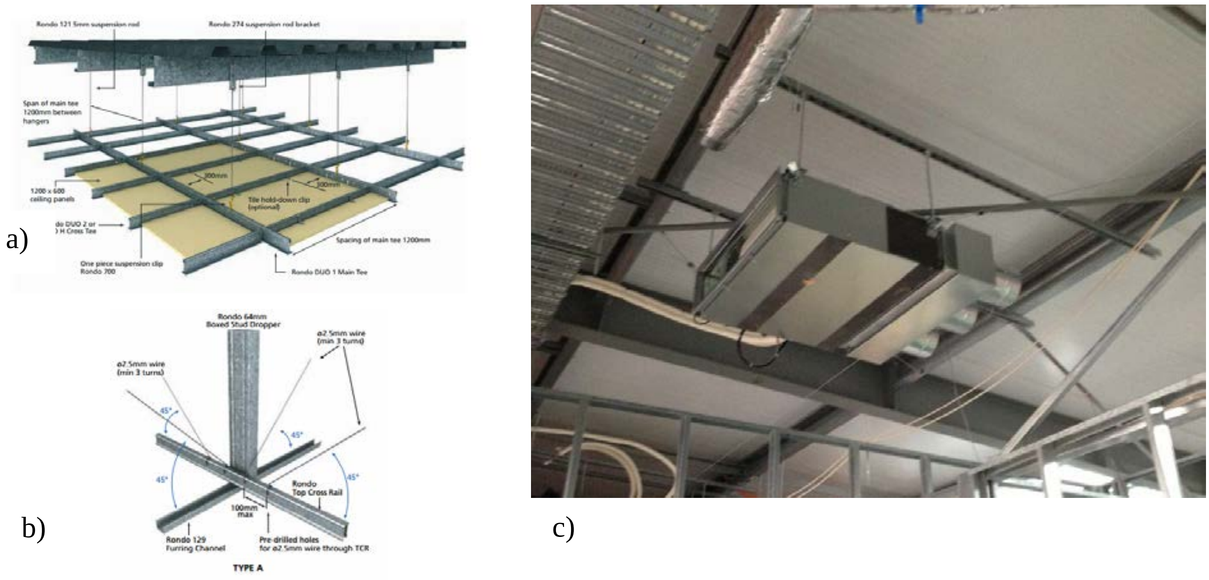

Figure 1. Typical overhead NSE details for: a) Rondo system typical construction, b) typical ceiling bracing, c) typical HVAC unit installation.

Overhead NSE’s provide a particularly direct safety hazard to building occupants. Falling elements, even of light weight, can cause injury to occupants as well as heightened emotional distress affecting perception of building performance.

The cost of repairing damage to overhead NSEs and consequential business interruption can be significant as demonstrated by recent earthquakes. Damage from earthquakes is typically dominated by non-structural elements, especially when the level of shaking is low as demonstrated by Bradley et al. 2009. The implications of this are concerning the insurance industry and have been addressed in a submission by the Insurance Council for the Building (Earthquake-prone Buildings) Amendment Bill, (Insurance Council 2014).

2 INJURY AND DAMAGE FROM RECENT EARTHQUAKES

Damaging earthquakes that occurred in Canterbury expectedly caused damage to overhead NSEs. Fortunately there were no known fatalities caused directly by these elements; however, there appear to have been many near misses. A report into the Social effects of the Canterbury earthquakes (Parliament Library 2014), notes that during the 4th September 2010 earthquake 377 people suffered injuries with over 1,000 injured in the aftermath. As a result of the 22 February earthquake there were 185 fatalities and 3,129 people injured with a further 1,293 people injured in the aftermath. It is stated that apart from physical injuries, psychological recovery can take five to ten years.

Whilst the authors have not found data on injuries related specifically to overhead NSE failures, in many instances during the Canterbury earthquakes, ceiling tiles were dislodged, HVAC units fell through the ceiling, and glass partitions fell onto desks as shown in Figure 2.

Damage that occurred to suspended ceilings typically comprised of grid damage, perimeter damage, and interaction with other elements as discussed in Dhakal and MacRae, 2013. Buckling of grid members and failure of perimeter connections, resulting in loss of support for the ceiling tiles was observed. This type of damage was caused by earthquake shaking in excess of the design loads and in many cases was caused and/or exacerbated by interaction with other equipment, adding significantly more weight to the ceiling system or due to displacement incompatibilities between connected items including ceilings, HVAC equipment, wall partitions, and perimeter walls.

Figure 2. Observed damage to overhead NSEs following the Canterbury Earthquakes; a) dislodged ceiling tiles and glass partition, b) HVAC unit fallen through ceiling, c) HVAC supports failed, d) failure of HVAC unit fixing, e) distortion of ceiling grid from wall, f) damage to ceiling tiles around sprinkler heads.

In some instances, similar damage to that observed in Christchurch also occurred in Wellington, following the Cook Strait earthquake sequence, at much lower earthquake intensity. The BNZ building in Lambton Quay displayed significant overhead NSE damage, causing costly repairs and business interruption. It was reported in the media that ceilings collapsed under the weight of unrestrained air conditioning ducts and sprinkler pipes, with ceiling panels falling on trading room desks. The cost of repairs was expected to be in excess of $10 million.

It is clear from the Canterbury and Cook Strait earthquakes that generally building structures performed as they were designed too, but fitouts failed causing significant damage. In addition, it is evident that building structures and NSEs should be designed and constructed consistently under a holistic approach to avoid disproportionate damage or safety hazards initiated by the weakest element.

3 CURRENT DESIGN AND CONSTRUCTION PRACTICE

Current design and construction of overhead NSE's generally adopts a 'Silo' type approach whereby each element is designed in isolation. There is limited interaction between designers/installers of different elements with limited information on the expected performance of the primary structure provided to NSE designers. Furthermore, there is a misalignment between Building Codes and the limited design Standards for overhead NSEs, with different standards for different elements.

A top down assessment of current codes and standards is described below from the New Zealand Building Act, Building Code, and Standards requirements.

3.1 New Zealand Building Code

The Building Act 2004 has the following purposes:

a) To provide for the regulation and the setting of performance standards for buildings to ensure that:

   i) People who use buildings can do so safely and without endangering their health; and

   ii) Buildings have attributes that contribute appropriately to the health, physical independence, and well-being of the people who use them; and

   iii) People who use a building can escape from the building if it is on fire; and

   iv) Buildings are designed, constructed, and able to be used in ways that promote sustainable development:

b) To promote the accountability of owners, designers, builders, and building consent authorities who have responsibilities for ensuring that building work complies with the building code

Whilst the above purpose statement would clearly cover overhead NSE's, **there is a noticeable absence of reference to overhead NSE's in the Building Code**. The focus is on the primary structure of buildings and the potential hazard from overhead NSE's is not emphasised. However, overhead NSE's are included in the NZ Building Code as building elements. Performance objectives are provided in Clause B1, which state:

- Buildings, **building elements** and sitework shall have a low probability of rupturing, becoming unstable, losing equilibrium, or collapsing during construction or alteration and throughout their lives.
- Buildings, **building elements** and sitework shall have a low probability of causing loss of amenity through undue deformation, vibratory response, degradation, or other physical characteristics throughout their lives, or during construction or alteration when the building is in use.

For the Seismic Design of Engineering systems, B1/VM1 cites NZS4219:2009 – Seismic Performance of Engineering Systems in a Building as a means of meeting the Code for overhead NSE's, subject to (Section 13.1); a minimum Z of 0.3 in the Canterbury Earthquake Region, and a minimum R_c of 0.33 in the Canterbury Earthquake Region.

NZS4219:2009 covers only seismic restraint of HVAC units and ducting, electrical units and pipework. There is a noticeable lack of reference to suspended ceilings as NZS 2785:2000 is not cited in B1/VM1, and **suspended ceilings are specifically excluded from NZS 4219:2009.**

3.2 New Zealand Standards

Currently, the following standards can be used for the design and installation of overhead NSEs:

- NZS 1170.5:2004 – Structural design actions Part 5 – Earthquake Actions Section 8 "Requirements for Parts and Components"
- AS/NZS 2785:2000 – Suspended Ceilings: Design and Installation

- NZS 4219:2009 – Seismic performance of engineering systems in a building.
- NZS 4541:2013 – Automated Fire Sprinkler Systems

To satisfy SLS requirements of NZS1170:2004, the structure and the non-structural components shall not require repair after an SLS earthquake, snow or wind event and the structure shall maintain operational continuity.

To satisfy ULS requirements of NZS1170:2004, a structure shall be designed and constructed in such a way that it will, during its design working life, with appropriate degrees of reliability sustain all actions and environmental influences likely to occur. Specifically, for earthquake actions for ULS this shall mean (NZS1170.0:2002 Clause 3.2):

(i) avoidance of collapse of the structural system;

(ii) avoidance of collapse or loss of support of parts of the structure representing a hazard to human life inside and outside the structure or parts required for life safety systems; and

(iii) avoidance of damage to non-structural systems necessary for the building evacuation procedures that renders them inoperative.

According to NZS 4541:2013, all sprinkler system components shall be designed, detailed, and installed so as to remain operational at the ULS earthquake loading for the sprinkler-protected building structure as specified in NZS 1170.5. The sprinkler system shall not be able to be damaged or impaired by the movement or failure of other features or components of the building. **There is no specific reference to SLS performance for sprinkler systems.**

Generally, current standards allow design of typical overhead NSEs to be carried out only to SLS loading as part category p7 (NZS1170.5, Section 8). Therefore, NSEs are designed for much lower loads than the building itself and the risk to injury, downtime and cost of repair is not appropriately acknowledged. Moreover, items up to 10kg suspended up to 3m above occupied areas are permitted under NZS4219:2009 (Clause 5.13) to be supported on the ceiling grid alone with no dedicated tie to supports above.

3.3 Design Issues

The design of overhead NSEs in a coordinated manner is made complicated by the following factors:

- The design is fragmented over a number of different disciplines with each item designed in isolation with a varying level of performance requirements for different elements.
- There are limited design standards with different standards for different items and definition of relevant building performance may be limited for NSE designers.
- Lack of transparency in design guidelines, particularly for ceilings where manufacturers' information on proprietary systems is relied upon.
- Suspended items weighing up to 10kg permitted to be up to 3m above occupied areas and supported only on the ceiling grid.

3.4 Construction Practice

In addition to the miss-alignment and gaps in the current design standards, there are also a number of discrepancies with current construction practice for overhead NSE's:

- The NZS 4219 recommended minimum clearances between the ceiling and equipment supported independently of ceilings are not always being adhered to in practice.
- Inappropriate connection of ceilings to suspended services (such as ducts), or a lack of ceiling support being provide around services.
- In some cases, there is a lack of inspection of a part of the building that may be perceived as of lesser importance than the primary structure.

Ceiling and services contracts are often awarded based on the lowest price. There is a lack of incentive to provide correctly designed, coordinated and installed seismic bracing. Typically, there is no mechanism for integrating the design allowances for all overhead NSE's before tender. Therefore, incompatibilities need to be resolved (or left unresolved) during the pressure of construction.

4 RECOMMENDED DESIGN AND CODE CHANGES

4.1 Objectives and Philosophy

It is recommended to treat overhead NSEs as a system similar to structures, and look at the three D's, Death, Dollars and Downtime discussed by various authors previously (Priestley et al. 2007, Dhakal 2011, Hare et al. 2012 etc.). For overhead NSE's "Death" is taken to include injury as the dominant effect, including mental health.

These three requirements to date have not been well satisfied. Whilst there have been no known deaths from overhead NSEs from recent earthquakes in New Zealand, that appears to have been from good luck more so than good management. Fatalities resulting from ceiling damage were recorded in the 2011 Japan earthquake (Dhakal et al. 2013). Furthermore, it has been identified that repair cost and business interruption can be significant, and out of proportion to the element importance/function in some cases.

4.2 Recommended Code/Standard changes

As discussed in Section 3, currently there is a misalignment of the Building Code and the various design standards for overhead NSE's. It is recommended to align the Building Code and NZ Standards to have consistent performance requirements and to cite the design of suspended ceilings. Amalgamation of the seismic requirements of current standards to form a single standard or section for overhead NSE's is suggested.

NZS1170.0:2004 states that, to satisfy SLS requirements, the structure and the non-structural components shall not require repair after an SLS earthquake. However, some readily repairable damage, such as buckled grids or slotted tiles may be tolerable, provided services remain functional (MBIE 2012).

The authors recommend that overhead NSE's be treated as a structural system and therefore, designed to the ULS requirements from NZS1170:2004, namely:

(i) avoidance of collapse of the structural system;

(ii) avoidance of collapse or loss of support of parts of the structure representing a hazard to human life inside and outside the structure or parts required for life safety systems; and

(iii) avoidance of damage to non-structural systems necessary for the building evacuation procedures that renders them inoperative.

To achieve these performance requirements, the seismic design of elements typically should be carried out to a higher level (ULS) than current code suggests, but could be moderated at SLS if damage is readily repairable, without loss of amenity. It is recommended that overhead NSEs be designed as parts that represent hazard to life for suspended ceilings and mechanical equipment, and a part required for operational continuity for fire sprinkler systems. Under NZS1170.5:2004 this represents P2 – P4 for suspended elements depending on the scale e.g. affecting crowds of more than 100 people.

It is noted that draft changes to NZS1170.5 have been released which amalgamate category P1 – P3 into one. Therefore, if adopted, this recommendation would require overhead NSE's to be designed as part P1. Moreover, the part risk factor R_p has been proposed in the draft changes to increase from 1.0 to 2.0 for part P1.

The authors recommend suspended items greater than 5kg be designed as P1 or P4 in a typical commercial structure. It is noted that current code (NZS4219:2009) allows elements up to 10kg to be supported on the ceiling grid alone, but even 5kg falling 3m can cause considerable damage or injury.

To assist in the design and installation of overhead NSE's in a coordinated manner, it is recommended that a performance specification be provided to all NSE sub-consultants at the time of design. The performance specification should include design parameters and displacements of the primary structure. It is intended that the same design build process currently in practice be continued with the performance specification providing a clear description of what is required from NSEs and putting contractors on a level playing field with respect to tendering. In addition, a period of coordination of NSE design prior to construction would reduce risk of inadequate clash resolution on site.

5 CASE STUDY

At the time of writing, the design of a four storey commercial building in Christchurch, New Zealand was being completed. As an example of how the recommended approach can be applied in current circumstances, the following performance specification for overhead NSEs was presented to the ceiling and services sub-contractors to assist in preparation of tendering and flagging allowance for coordination of services.

5.1 Scope

The scope of this specification is for the performance requirements of seismic restraints for suspended non-structural elements, including all proprietary suspended ceiling systems, mechanical services plant, and any other above ceiling services.

5.2 Materials and workmanship

All design, materials and workmanship shall comply with the requirements of the NZ Building Code, except as modified by this specification. Materials and proprietary systems shall also be supplied and installed in accordance with the manufacturer's recommendations.

5.3 General Seismic Design Parameters

For the purposes of determining the seismic load acting on all non-structural elements, including all proprietary suspended ceiling systems, mechanical services plant, and any other above ceiling services, the following parameters shall be used in accordance with NZS1170.5:2014 and NZS4219:2009:

- Building location Christchurch, New Zealand (Z=0.3 shall be used, note NZS4219 currently states Z=0.22 for Christchurch)
- Soil class D
- Building Importance Level 2
- Structure period T = 0.7s
- Ultimate Limit State loading for category P1 - *"Part representing a hazard to individual life within the structure"*. Note, R_p =2.0 in accordance with NZS1170.5:2014, and R_c =2.0 using NZS4219:2009
- Maximum horizontal inter-storey displacement of **60**mm (at 3.0m height)

All non-structural elements shall be designed for the part risk factor and limit state as defined for category P.1 – see Table 8.1 (NZS1170.5:2014 Draft). Note, the design parameters stated in this section may be in excess of the requirements of NZS1170.5:2004, NZS4219:2009 and AS/NZS 2785:2000.

5.4 Suspended Ceiling

The suspended ceiling system shall be designed in accordance with the requirements of AS/NZS 2785:2000. Seismic loading acting on the ceiling shall be determined in accordance with NZS1170.5:2014 Structural design actions – Part 5: Earthquake actions – New Zealand.

For the purposes of seismic design, the ceiling system shall be designed for the parameters described in section 5.3. Note, the design parameters above may be in excess of the requirements of NZS1170.5:2014 and AS/NZS 2785:2000. The ceiling shall not be braced by partition walls.

A service load of at least 3kg/m^2 shall be included in the lateral bracing design of the ceiling. The ceiling tiles shall weigh a maximum of 4kg/m^2.

Any items supported within the ceiling grid weighing in excess of 5kg shall be provided with independent vertical restraint, refer to section 5.5.

Allowance shall be made for coordination with other services and resolution of any conflicts prior to construction.

5.5 **Mechanical and Electrical Services**

Independent seismic restraint of mechanical and electrical services shall be provided in accordance with the requirements of NZS4219:2009 and/or NZS1170.5:2014. For the purposes of design, seismic restraints shall be designed for the parameters described in section 5.3.

Any items within the ceiling plenum weighing in excess of 5kg shall be provided with independent vertical restraint. Note this is in excess of the requirements of NZS4219:2009. Any services weighing in excess of 3kg/m2 shall be provided with independent seismic restraint.

Allowance shall be made for coordination with other services and resolution of any conflicts prior to construction.

5.6 **Fire Sprinklers**

Design of seismic restraints for sprinkler systems shall be in accordance with NZS4219:2009 and the parameters stated in section 5.3.

Sprinkler head penetrations through the suspended ceiling shall have a 50mm oversize ring, sleeve or adapter to allow free movement of at least 25mm in all horizontal directions.

Allowance shall be made for coordination with other services and resolution of any conflicts prior to construction.

5.7 **Wall partitions**

Wall partitions shall be braced from the structure and be independent from other suspended elements. The suspended ceiling shall not be used to brace wall partitions.

5.8 **Fixings and Attachments**

Components shall be fixed or attached to the supporting structure so that seismic forces are transferred to the structure. Such fixings shall be designed to be positively restrained without consideration of frictional resistance. Ensure positive fixings between supports/restraints and suspended items.

All fixings shall be "rigid" unless agreed otherwise with the Engineer. Rigid fixings include members such as angles acting in compression and steel ties designed for tension. Connection points shall also be designed to carry the design loads without significant deflection (less than 2mm).

6 **CONCLUSION AND RECOMMENDATIONS**

This paper discusses the seismic design of interior overhead non-structural elements (NSEs) in buildings with reference to current NZ Building Code and Standards requirements and current construction practice.

Safety and damage avoidance philosophies have been identified and a performance specification for a case study building was presented. The following recommendations are made to be incorporated into changes to current standards and construction practice:

1. Move away from “silo” approach to both design and construction. Effective outcomes require an integrated approach for overhead NSE’s.
2. Review and align relevant parts of Building Code and Standards, particularly:
    a. Create a new section in the Building Code for overhead NSE’s, to align with the purpose of the Building Act.
    b. Review means of compliance of existing Standards to align SLS and ULS design requirements.
3. Raise standards where recent observations of EQ damage indicates they are inadequate, such as the current limit for unsupported elements in suspended ceilings which allow up to 10kg up to 3.0m above occupied spaces.

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