Seismic performance of suspended ceilings: Critical review of current design practice

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ABSTRACT: Recent experiences have shown that ceiling damage can result in property and functionality loss, injury or even death. This can occur at levels of shaking smaller than those required to produce noticeable structural damage. Despite their frequent use in New Zealand, many suspended ceilings that experienced damage in the past earthquakes lacked either proper seismic design or efficient installation. There is also an increasing concern about the inconsistency of the limit state applied for the design of ceilings.

This study looks into the gaps and issues currently present in the seismic design and installation of suspended ceilings in New Zealand. In order to provide an inclusive background, the existing standards and guidelines for design and installation of ceilings both available in New Zealand and worldwide have been reviewed. Through this comparative study, areas of similarity and discrepancy have been identified, along with the ambiguities and gaps which define the extent of research required. Investigations have also been performed on the seismic design approaches of proprietary suspended ceilings. This study mainly addresses the residential and commercial suspended ceilings provided by two major ceiling manufacturers in New Zealand. The capacity of either ceiling system has been evaluated through component based fragility studies. The comparison of the current systems' capacity with the New Zealand code prescribed demand provides an objective understanding of the performance of the existing system. Moreover the efficiency of the assigned design limit states can be better evaluated.

1 INTRODUCTION

1.1 Suspended ceilings structural system

Suspended ceilings are architectural components sensitive to both acceleration and displacement (FEMA 2011). Depending on the structure and load bearing system, they are categorised as perimeter-fixed or floating systems. The perimeter-fixed suspended ceiling, as shown in Figure 1a, is fixed to the surrounding structure on all sides. This configuration was later modified to fixing on two adjacent sides while the other two opposite ends are free to slide on the perimeter support (Fig. 1b). In this configuration the inertial force induced in the ceiling system is transferred to the perimeter fixings, making these connections the most vulnerable components of the system. The floating suspended ceiling, shown in Figure 1c, is supported to the structure above via braces and therefore is disconnected from the surrounding structure. The bracing system bears the forces and accelerations transferred from the floor above.

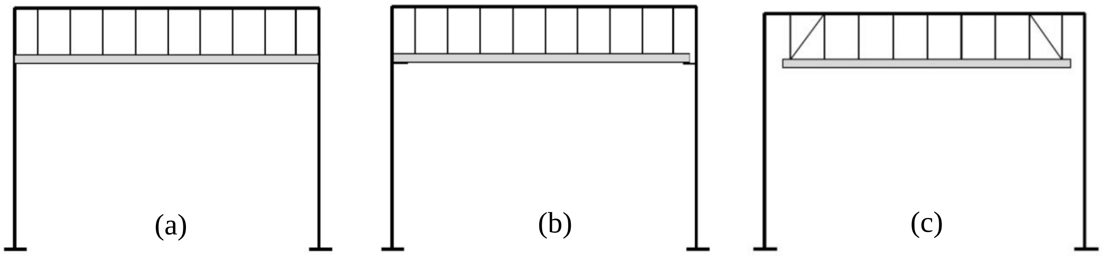

Figure 1. Schematic of a&b) Perimeter fixed and c) Floating suspended ceiling

The applicability and details of either system depends on the seismic demand on the structure as well as the size of the ceiling. For instance, ASTM E580 mandates the application of lateral restraints for all suspended ceilings in seismic category D-F, should the size of the ceiling exceed 1000 ft^2 [93 m^2].

A typical suspended ceiling consists of a grid system of inverted T-shaped beams assembled perpendicular to each other forming square or rectangular grids for the lay-in panels to sit on (Fig. 2a). The grid system consists of 3600mm long main tees and 600 or 1200mm long cross tees. In case of shorter direction of the ceiling-Main tee direction- exceeding 3600mm, the main tees are extended via splices. Cross tees pass through the special slots previously built in the main tees webs and are connected to the next cross tee via click-fit connections. No additional mechanical fasteners are used in the assembly of the grid system itself. On the fixed ends, the grid system is connected to the perimeter angle fastened to the surrounding walls using mechanical fixtures such as rivets, screws or special clips. The lay-in tiles are not fastened to the grids but rather sit freely on the inverted tee flanges. AS/NZS 2785 recommends the use of retainer clips to control the upward movement of the tiles. However, these clips are not very commonly used due to the difficulties in installation. The grid system is also hung from the structure above via hanger wires connected to main tees at certain intervals. These vertical wires don't have any lateral resistance but their application, particularly on perimeters, has proven advantageous in limiting the movement of the ceiling system and the consequent damage in earthquakes. The bracing can consist of four diagonal wires and a vertical strut performing as a compression post. Diagonal channel or strut members can also be used instead of the wires (Fig. 2b).

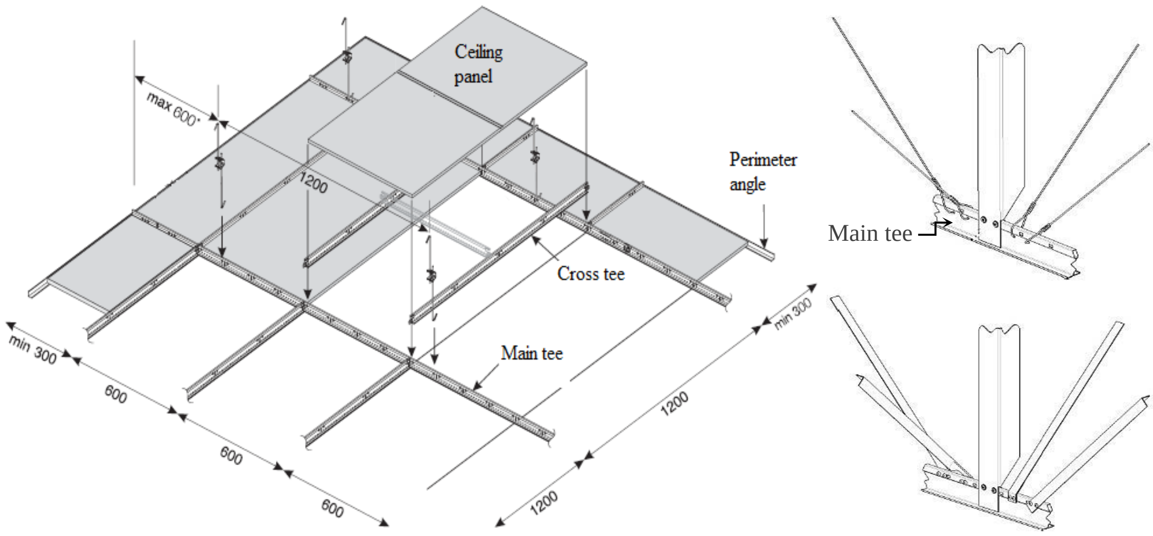

Figure 2. a) (Left) Typical suspended ceiling components by Armstrong (2013); b) (Right) Typical back bracing options by USG (2012)

1.2 Ceiling damage in recent earthquakes

According to damage reports following previous earthquakes and particularly the recent ones in New Zealand, suspended ceilings suffer considerable damage in earthquakes even when the structure remains almost undamaged. The damage incurred follows a similar pattern in almost all cases which can be a great hint in identifying critical components. The elements showing considerable vulnerability to ground motion excitation include rivet connections at perimeter fixings, connections between cross tees and splices in main tees. There is the possibility of buckling of tees under compression but the system mainly loses integrity when connections fail or the perimeter ledge size provided for supporting the tees is insufficient. In some cases, the absence of sufficient perimeter hanger wires and spacer bars causes spreading of tees and downfall of tiles. Other common forms of damage observed include damage due to the differential movement of ceiling relative to the structure at perimeters or vicinity of rigid penetrating elements such as columns or sprinkler heads, interaction with services and mechanical systems above the ceiling or heavy fixtures lacking independent support, post-earthquake damage caused by fire, hazardous material leak etc. A combination of smaller ceilings and lighter tiles is reported to result in lower demand on the grid members and connections, which leads to safer ceilings (Dhakal 2010, Dhakal et al. 2011).

2 PREVIOUS STUDIES

Seismic research on the performance of non-structural elements and suspended ceilings in particular has gained popularity in recent decades, following the extensive non-structural damage reported in recent earthquakes. A brief review of some of these studies follows.

The industry-sponsored tests by ANCO Engineers Inc. (ANCO 1983) on a prototypical suspended ceiling concluded that the most common locations for damage in suspended ceiling systems were around the perimeter of a room at the intersection of the walls and ceilings, where the runners buckle or detach from the wall angle. Their research also showed that pop rivet installation is more influential than sway wires and that sway wire braces, if installed with perimeter fixing, will not be active in the system's lateral restraint.

Rihal et al. (1984) investigated the effectiveness of current building code provisions and installation practices for braced and unbraced suspended ceilings with and without partitions in a series of dynamic tests. According to their results, specimens with vertical strut showed less uplift. Extensive damage to ceiling was observed at unattached perimeter. Addition of vertical suspension wires at cross tees at 8 inch max from unattached perimeter prevented tiles from crashing down but damage was caused by pounding of cross tees to perimeter angles.

Badillo-Almaraz et al. (2007) conducted fragility studies on suspended ceiling systems. In their full-scale earthquake-simulator testing they evaluated the effect of size and weight of tiles, use of retainer clips, installation of compression posts, and physical condition of grid components on the performance of ceilings. Four limit states were proposed to evaluate the damage observed in the systems and the threshold peak floor accelerations associated with each limit state were found.

In a series of studies by Gilani et al. (2010, 2012) and Glasgow (2010), an experimental procedure and a performance matrix based on limit states were developed to evaluate and qualify innovations and quantitatively assess the efficacy of various code prescribed design and installation requirements. Fragility curve for panel failure as one of the damage states was derived. The use of intermediate duty main runners in high seismic regions was also tested through a case study which showed that the substitution of intermediate for heavy-duty main runners does not adversely affect the seismic response of the system.

In a research carried out by Paganotti (2010) at University of Canterbury, grid members and their connections were tested in compression and tension. Failure loads from the tests were used for derivation of fragility curves for the components and identification of the most critical elements of the ceiling. These results were then applied in conjunction with simple modelling of the ceiling system to derive fragility curves for suspended ceiling system.

3 CURRENT DESIGN AND INSTALLATION APPROACH

3.1 Demand on structure vs. ceiling

In New Zealand, various structures depending on their application and importance level are designed to satisfy serviceability and ultimate limit states requirements. Based on current standards in New Zealand (NZS 1170.5 2004), suspended ceilings are mainly designed for serviceability limit state unless they are located in buildings of high post-disaster significance e.g. hospitals and police stations. However, recent seismic experiences have proven that damage to suspended ceilings can pose a life threat and cause considerable financial loss. In many cases while the structure's performance was satisfactory, suspended ceilings underwent considerable damage. The inevitable replacement then imposes large financial costs to the building owners and interrupts the operability of the building leading to downtime and inconvenience. In many buildings assessed after the Canterbury earthquake (Dhakal 2010 & Dhakal et al. 2011), ceilings were reported to have been designed without proper consideration to seismic demand or were not properly installed which can be due to the absence of a consistent and clear design and installation guideline for suspended ceilings. Even in cases which fully complied with the requirements, ceilings were damaged as they were basically not designed to remain intact under that level of shaking.

Suspended ceilings do not inherit a great level of ductility. Hence the point where the system loses its originally intended operation -SLS- and the point where it loses integrity and undergoes collapse, thereby endangering occupants -ULS- are rather close. Therefore, the reconsideration and thorough evaluation of the design and installation practices in New Zealand seem inevitable and highly beneficial in prevention of future loss.

3.2 Standards review

New Zealand standard for suspended ceilings (AS/NZS 2785:2000) sets out the minimum requirements for the design, construction, installation, maintenance and testing of internal and external non-trafficable suspended ceilings for use in commercial, industrial and residential buildings. The standard includes the design loads, definition of limit states and installation recommendations. However, the recommendations are mainly qualitative rather than specifying quantitative limits. In many cases the users are referred to the proprietary manufacturers' specifications.

New Zealand structural design standard for earthquake actions (NZS 1170.5:2004) has a section specified for the design of parts and components. In this section recommendations are provided for calculating the seismic design action on suspended ceilings. According to these specifications suspended ceilings are mostly classified in a category (P7) which requires serviceability limit state design.

Other standards such as ASTM C635, C636 and E580, ASCE 7-05, FEMA and CISCA provide more quantitative guidelines for the seismic design and installation of suspended ceilings. For instance, CISCA for seismic zones 3&4 proposes the installation of 45-degree sway bracing wires in each direction at 4m centre to centre. These wires are to provide resistance for the horizontal component of the earthquake force. In addition, to reduce ceiling perimeter damage, hanger wires are required within 20cm of a wall for all runners abutting the walls.

ASTM E580 provides specifications for the installation of suspended ceilings in areas of seismic category C as well as categories D-F which includes the capacity of tees, proper spacing of hanger wires, clearance of grid members from the walls, the size and type of perimeter support ledge -fixed or free- etc.

3.3 Proprietary suspended ceiling systems

Currently suspended ceilings in New Zealand are provided by a limited number of major manufacturers, two of which have been studied in this paper. These proprietary manufacturers each provide their own specific design and installation guidelines which should be closely complied with by the users and contractors.

As stated in their New Zealand specified seismic design guide, both manufacturers design ceilings to meet the requirements of NZS 1170.5 – Structural Design Actions – Earthquake actions. Since NZS 1170.5 (Section 8), classifies ordinary ceilings as category P7, these ceilings shall be designed to satisfy serviceability limit state criteria. Therefore, it is concluded that ceilings designed according to their design guidelines are only expected to withstand a serviceability level earthquake with 25-year return period. One of these two manufacturers also provides guidelines for design of suspended ceilings for both serviceability and ultimate limit states.

They both provide expressions for calculating the seismic force in the ceilings. The expressions take into account the seismic zone factor, ceiling height factor, ceiling slope factor and ceiling weight including service load. The main and cross tees and fixing types have a certain capacity which is then used along with the seismic force calculated to determine the allowable length of the tees in each direction and eventually the possible size of the ceiling. They also provide options for bracing the system which include 1) perimeter fixing of adjacent edges, 2) perimeter fixing on more than two edges while the ceiling is split up using seismic joints -for areas larger than $232m^2$- and 3) back bracing with free sliding joints on all perimeter edges -for areas larger than $93m^2$. The bracing is provided using compression struts with diagonal tension wire braces or diagonal tension/compression struts.

3.4 **A sample ceiling design**

In order to carry out a comparative evaluation of the two proprietary design guidelines, a sample suspended ceiling is designed following the methods provided by both manufacturers' seismic design guidelines. The ceilings are assumed to be located on different floors of a building located in Christchurch. Heavy panels of the same weight (10kg per panel) have been used. A minimum service load of 3kg/m^2 and a constant value of 1kg/m^2 for grid weight have been added to the ceiling weight to make up the seismic mass. The period of the ceilings is assumed less than 0.75s according to the design guide and their ductility is assumed to be μ_p=1. Ceilings are not back braced and 3.2mm Aluminium rivets are used on the fixed perimeters. Grid members were chosen to be as similar as possible in the two systems.

The code mandated seismic demand is calculated based on the specifications of NZS 1170.5:2004, Section 8 for parts, for a structure built on soil type C and a 25-year return period earthquake - serviceability limit state design.

Horizontal acceleration coefficient at the level of supporting structure is determined as:

$$C_P(T_P) = C(0)C_{Hi}C_i(T_P) \quad (1)$$

Where C_{Hi} is floor height coefficient, varying between 2 to 3 for levels 2-4 and higher, $C_i(T_P)$. The part spectral shape factor is 2 assuming that suspended ceilings have a period less than 0.75s. C(0) the site hazard coefficient for T=0 using the values for parts, is calculated as below:

$$C(0) = C_h(0)ZRN(T,D) = 0.132 \quad (2)$$

$C_h(0) = 1.33$ Part Spectral Shape Factor – Site Subsoil Class C for Christchurch as the worst case scenario

$Z = 0.3$ Hazard Factor for Christchurch according to (DBH 2011). ("The minimum hazard factor Z for the Canterbury earthquake region shall be 0.3")

$R_S = 0.33$ Return Period Factor for SLS1 according to (DBH 2011). ("In the Canterbury earthquake region, the risk factor for the serviceability limit state shall not be taken less than R_s = 0.33.")

$N(T,D) = 1.0$ Near Fault Factor – 1.0 for Christchurch (D > 20 km)

Figure 3 shows the values of horizontal seismic force calculated for the above mentioned ceilings supported on various levels of the building. As it can be observed, the values of seismic force based on proprietary design guidelines and the code are almost identical. Table 1 shows the horizontal acceleration coefficients calculated based on equation 1 and the design guidelines.

Using the seismic force values in figure 3, ceilings were designed according to the two proprietary system methods. The allowable length of main tees and cross tees based on the proprietary guidelines seismic force as well as the SLS seismic demand based on NZS 1170.5 were calculated and were found to be very similar as expected, since the values of seismic force are almost the same.

Although both guidelines design the ceilings for serviceability limit state, in order to get an idea of the probable performance of the designed ceilings when subjected to an ultimate limit state earthquake (i.e. DBE), the seismic demands based on a 500-year return period earthquake have also been calculated for comparison. Evaluation of the designed ceiling is carried out using the ceiling fragility curves derived based on component test results (Paganotti 2010). These fragility curves were created following numerous tests on the suspended ceiling components provided by the two aforementioned manufacturers. After comparing the curves, the most critical components having the lowest failure forces were chosen as the elements governing the capacity of the ceiling. Figure 4 shows the fragility curves for the designed ceilings on level 4. The vertical lines on the graphs show the calculated code demands for serviceability and ultimate limit states.

Table 1. Horizontal acceleration coefficients

	Level 2	Level 3	Level 4	Level 5
Code	0.527	0.658	0.790	0.790
System 1	0.527	0.657	0.792	0.792
System 2	0.536	0.674	0.795	0.795

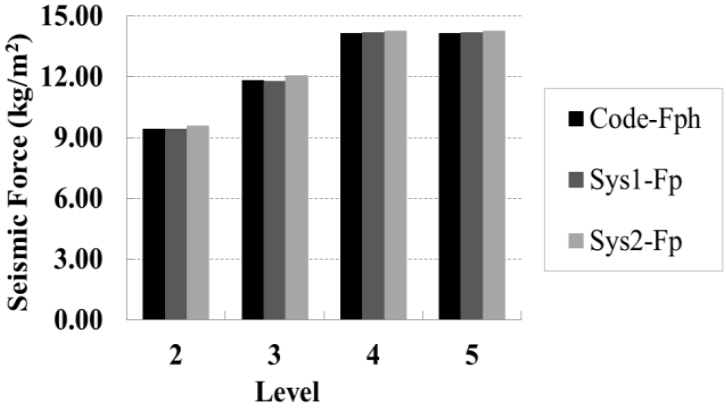

Figure 3. Values of seismic force based on various design guides

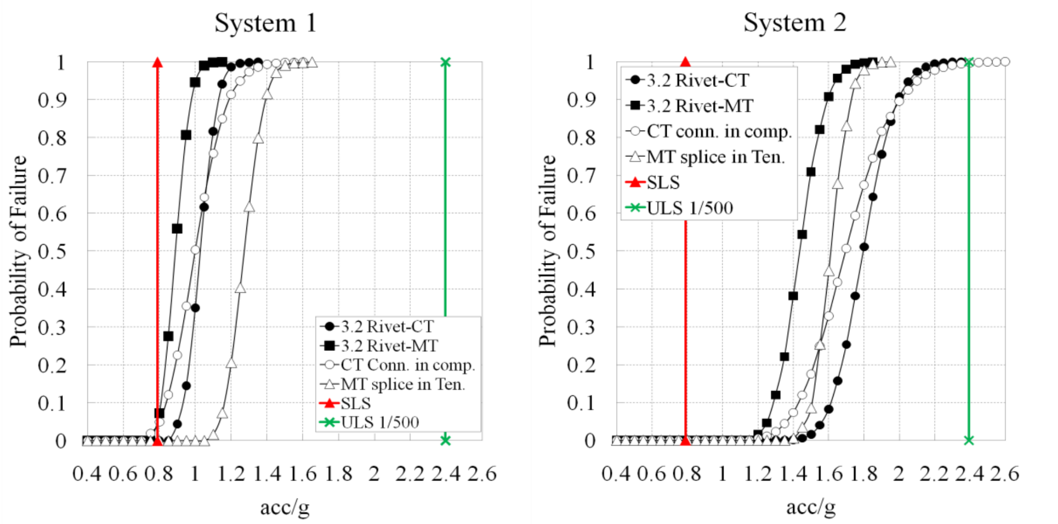

Figure 4. Fragility curves for the level 4 ceilings

CT=cross tee, MT=main tee, CT Conn in Comp.=cross tee connection in compression, MT splice in Ten.=Main tee splice in tension, 3.2Rivet-CT=3.2mm rivet on cross tees, 3.2rivet-MT=3.2mm rivet on main tees

As it can be observed in the fragility curves, both systems will certainly not fail in the serviceability level acceleration. However when compared with the ultimate level excitation demand, the probability of failure is 100%, i.e. failure is inevitable. Due to the larger size of the ceiling designed in system 1, the median values of acceleration are lower in all elements in system 1, showing that this ceiling is more vulnerable when subjected to an earthquake compared to the one designed by system 2. However, when ceilings designed in both systems are of the same size, the capacities and therefore failure accelerations will be similar.

4 ISSUES AND GAPS

According to Clause 8.1.2 of NZS 1170.5:2004, majority of ceilings which are of ordinary importance level, fall under category P7. These ceilings are required to be designed to remain undamaged under SLS1 earthquake. It is not clear whether or not these requirements also satisfy the AS/NZS 2785:2000 Ultimate strength requirements. The categories defining the applicability of either limit state are somehow overlapping or can be interpreted differently. Also, even if the stated requirements are clearly understood, it is not clear if they are adequate. For example, following the 2010 earthquakes in New Zealand, building owners had to replace ceilings several times resulting in a high economic cost. This indicates the need for reconsideration of design requirements. A different level of safety may be appropriate.

New Zealand code for the design and installation of suspended ceilings (AS/NZS 2785:2000) Clause 3.1.2 states that "Ceiling systems should be designed and installed to … remain structurally sound, without maintenance, for a period of 15 years". On the other hand, in calculation of return period factor for the design earthquake actions on ceilings, both for serviceability and ultimate limit states, the design working life of the building is considered. This could lead into inconsistencies and the level of safety required is not specified.

As long as the clear borderlines in safety and performance requirements are missing, it will be difficult to monitor and assess the quality of the systems presented to the market. Therefore it will be easier for some suppliers or installers to use poor materials or schemes that do not fully satisfy minimum safety and durability requirements. In order to reach a consistent level of quality and safety, the design and installation methods must be coordinated. This way, all products will be presented meeting minimum requirements and will satisfy similar levels of performance.

5 CURRENT AND FUTURE RESEARCH PLANS

Currently research on the seismic performance of suspended ceilings is under progress at University of Canterbury. Two major goals of this project are to improve the understanding of seismic resistance mechanism of suspended ceilings and to prepare a consistent and clear guideline for the design and installation of suspended ceilings in New Zealand. Experimental test programs and analytical modelling are currently planned to systematically investigate the performance of suspended ceilings when subjected to floor acceleration. Preliminary experiments have also been carried out to investigate the possibility of an alternative suspended ceiling system (Robson et al. 2014), and further experiment in this area is also programmed as part of this research project.

6 CONCLUSIONS

Damage to suspended ceilings, as one of the most commonly used non-structural components, has led to considerable financial loss in the recent earthquakes. This observation has directed lots of attention in recent years towards research programs on their seismic performance and design. In this paper, the available studies, guidelines and standards regarding the design and installation of suspended ceilings have been briefly reviewed. A simple comparison of the capacity of the suspended ceilings commonly available and used in New Zealand with the code mandated demands has been carried out. The comparison proves that the current system, if properly installed, should perform satisfactorily under serviceability level earthquake. However, in case of larger excitations the critical components may reach their capacity leading to system failure. Considering the significance of ceilings in maintaining continuous operation and safety in structures, reconsiderations in the code mandated limit states for the design of suspended ceilings seem inevitable. The preliminary results of this study along with the evaluation of the available codes show the criticality of the issue and necessity of more extensive and focused research in this area.

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