Feasibility of a fully floating ceiling system

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ABSTRACT: Recent Canterbury earthquakes have proven the inadequacy of the seismic design of current suspended ceilings. Significant financial loss was reported following the earthquake, as buildings were marked inoperable and businesses were interrupted during massive ceiling repairs or replacements. This highlights the need for an alternative ceiling system which is capable of avoiding losses of similar scale in future earthquakes.

This paper presents research undertaken to investigate the feasibility of a 'fully-floating' ceiling system design. The system incorporates an unrestrained ceiling, suspended from the floor above via steel wires. These steel wires, effectively having no lateral stiffness, allow for the safe dissipation of seismic energy. The flexibility also prevents the transfer of seismic forces from the floor above to the ceiling grid, resulting in minimal stresses sustained by the ceiling grid during ground excitations. However, there will invariably be relative displacement between the floor and the ceiling. Gaps will hence need to be provided around the perimeter of the ceiling to accommodate the building's drift movements. The system was modelled using simple pendulums. Effect of suspended mass, hanging length, excitation frequency and excitation amplitude on ceiling's performance was evaluated. Analytical and experimental models were subjected to seismic excitations and qualitative conclusions were drawn on correlations between these factors and the likely response of a fully floating ceiling.

Based on the results obtained, the proposed system at this stage looks feasible and able to meet the design requirements stipulated in NZS1170.5. The preliminary investigation indicates the need of a 0.15 m perimeter gap together with an elastomeric strip provided to limit damage in case the ceiling displacement demand exceeded the clearance provided.

1 INTRODUCTION

Building assessments following the 2011 Canterbury earthquakes reveal that current suspended ceiling systems in New Zealand handle seismic activity extremely poorly (MacRae *et al.* 2011).The failure and subsequent collapse of a ceiling not only poses a major threat to the lives of the building's occupants, but also leads to substantial financial losses. These losses can make up to 14% of a building's total repair cost for a representative RC office building as shown by Bradley (2009) and are then even further compounded by the loss of functionality of the building even when the structural integrity is intact.

The type of seismic damage sustained by a ceiling varies between buildings. However, common trends include one or the combination of the following; Grid damage, Perimeter damage, Tile dropout and Interaction with mechanical services.

There currently exist two main types of suspended ceiling systems. These are the 'floating' and the 'perimeter-fixed' systems shown in Figures 1a and 1b respectively. Perimeter-fixed ceilings extend to the wall face and are attached to two adjacent walls (or to all four walls in some cases) by means of a riveted angle connection fixed to the surrounding structure. The ceiling grid is also hung by steel wires attached to the floor above. Floating ceilings, on the other hand utilise the same suspended mechanism but are instead braced to the above structure, using angled members. Both ceiling systems use fully-

fixed lateral bracing connections. These connections allow for the accumulation of seismic forces along the ceiling grid and/or the braces, which are then transmitted to the surrounding wall (in perimeter-fixed systems) or the floor (in floating systems). If these forces are strong enough, damage will result in the ceiling members. It is therefore clear that revisions to ceiling system design are needed in order to prevent the hazardous manner in which current systems respond when subjected to seismic excitations.

The proposed 'fully-floating' ceiling system, shown in Figure 1c, builds on the current floating system. It excludes the angled brace connections to allow the ceiling to act as a simple pendulum; with the underlying concept being that ceiling suspension wires are designed to take the axial load but will have negligible lateral stiffness. Then, according to classic pendulum mechanics, none of the forces induced in the floor slab above will be transferred to the suspended ceiling mass. Also, as the lateral stiffness is zero, fundamental principles of structural dynamics indicate that the ceiling should not experience any absolute displacement and will essentially remain in the same position.

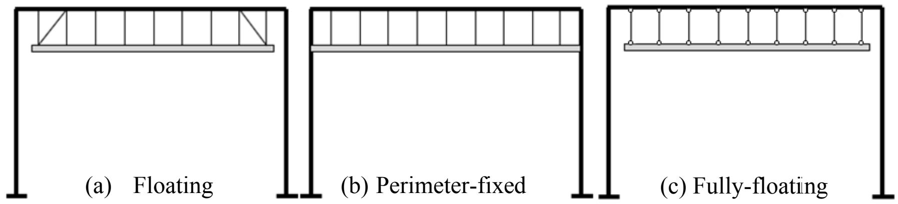

Figure 1. Suspended ceilings types

Provided that sufficient gaps are present on the outer edge of the ceiling to accommodate the building's inter-storey drift displacements, there should be no contact between the ceiling edge and perimeter walls. Without this contact, there can be no transfer of seismic force to the wall and ultimately no damage will occur in the ceiling or perimeter walls. However, the authors suspect that a pendulum mass hung by a laterally flexible wire may not actually remain undisturbed (as predicted by dynamics theory) when subjected to dynamic excitations at the support. Another main issue associated with this concept is the phenomenon of resonance. If the frequency of an excitation is close enough to that of the pendulum's natural frequency, then displacement amplification may occur.

The goal is hence to investigate the architectural and structural practicality of the proposed system in withstanding seismic excitations. This was done by conducting a series of preliminary tests to firstly gain an understanding of how various parameters such as mass, hanging length, excitation amplitude and excitation frequency affect a simple model of the fully floating ceiling system. The key factor in determining the feasibility of the design is the peak displacement response of the model under seismic excitation. The design will be considered feasible if the displacement responses are small enough to be contained and the hanging length is within a practical range.

2 MATERIALS

Both analytical investigations and experimental tests were conducted on a fully-floating ceiling system model. However, as a preliminary investigation a few simplifications were made to the model.

It was firstly assumed that each hanging wire along with its suspended panel could be approximated as a pendulum mounted from the floor above, as shown in Figure 2. The collective mass of the ceiling tiles and grid were then considered as the lumped mass of the pendulum.

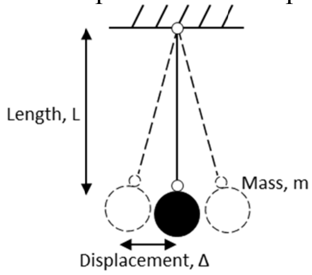

Figure 2. Ideal simplification of fully-floating ceiling system

The second simplification was to only consider one-directional motion to reduce the time requirements of modelling, analysis and testing. This would also eliminate torsional effects which are difficult to model and quantify from a technical perspective, and arguably not required at this stage. Furthermore, the ceiling was assumed to be mounted on a rigid one-storey frame to avoid the inclusion of errors due to the effect of structural properties on acceleration propagation along height.

2.1 **Analysis**

The ceiling model shown in Figure 2 was analytically modelled using the Open System for Earthquake Engineering Simulation (OpenSees) software developed by McKenna *et al.* (2006) at the University of Berkeley. Ground motion excitations of the PEER format were applied to the model.

2.2 **Experiment**

The experimental setup of the pendulum model involves the use of the hydraulic shake-table at the University of Canterbury. The apparatus consists of incremental barbell weights, steel wire and fluorescent stickers required for the motion-tracking of the system. The wire is attached to the steel frame assembled on the hydraulic shake-table. It was then fed through a small hole before being looped around itself to create a simple pin joint. The shake-table is capable of replicating uniaxial pre-recorded ground motion excitations as well as sinusoidal excitations within certain displacement and velocity limits. Testing schedules were carried out to investigate the effects of the parameters identified in Section 1, on the behaviour of the system; specifically the maximum displacement response and corresponding period of oscillation. All trials were recorded with a high-speed digital camera, which were then analysed using motion-tracking software developed by Hendrick (2008). The raw data produced from the motion-tracking software was then further analysed in Microsoft Excel to obtain displacement response histories for the suspended mass.

3 **METHODOLOGY**

Pre-recorded earthquake acceleration histories were obtained from the PEER Ground Motion Database (2011). Ground motions shown in Table 1 were chosen from a wide range of locations, dates and magnitudes so as to encompass variations in the local soil condition and fault type.

Table 1. Ground motion records used in testing

Location	Year	Richter Scale Magnitude	Record PGA (g)
Chalfant Valley	1986	5.8	0.06
Chi Chi	1999	7.5	0.15
Coalinga	1983	6.4	0.23
Edgecombe	1987	6.6	0.04
Imperial Valley	1940	6.9	0.31
Kobe	1995	6.9	0.03
Livermore	1980	5.8	0.07
Loma Prieta	1987	6.9	0.10
Lyttelton	2011	6.3	0.49
Mammoth Lakes	1980	6.1	0.42
Northridge	1994	5.1	0.01

3.1 **Analytical Modelling**

An OpenSees command file was written to model the pendulum approximation of the ceiling. The model contained a fixed displacement node which was free to rotate about one axis, representing a point on the one-storey rigid frame from which a hanging wire would be attached. A second node was then located directly below the first at a specifiable distance free to move both horizontally and vertically, to represent the lumped pendulum mass. The distance between the second and the first node represented the pendulum length. The two nodes were connected by a 'truss' element which was assigned the properties of a typical steel wire. The wire was given negligible stiffness in compression to mimic 'slack'. The pendulum length was set to 0.5m. A mass of 10kg was used to represent typical 600 by 600mm lightweight ceiling tiles weighing approximately 5kg with a hanger spacing of 0.9m. The model was then subjected to the ground motions shown in Table 1, with the excitations being applied at the pendulum base. In a real ceiling these excitations however will not be exactly the ones induced by the earthquake motion, as the structure modifies them when transferring the motion in height and through different elements. The lateral displacement of the pendulum mass, the base reaction force as well as the axial force within the pendulum were recorded for each simulation.

3.2 **Experimental Testing**

The four factors suspected to affect the behaviour of the pendulum system were each investigated separately.

Mass

The suspended mass values tested were 3kg, 5kg and 7.5kg. This range was specifically chosen to represent the varying weight of the ceiling tiles and hanger spacing. A constant wire length of 0.5m was used throughout the investigation.

For each individual mass, the excitations applied by the shake-table were:

Livermore - Scaled to 0.1g, 0.3g, 0.5g, 0.7g

Lyttelton - Scaled to 0.1g

Excitation Amplitude

For a pendulum system with a constant mass and length of 5kg and 0.5m respectively, the Livermore ground motion excitation was scaled down to 0.1, 0.3, 0.5, 0.7 and 0.07g (unscaled) to investigate the effects of different excitation acceleration amplitudes on the response of the suspended mass. The procedure was also repeated with a different mass of 3kg.

Length

The experiments concerning the effect of pendulum length involved the testing of five different wire lengths ranging from 0.2m to 1.0m in 0.2m increments. A constant weight of 5kg was maintained throughout the experiments. For each length, the ground motions applied were;

Loma Prieta - Scaled to 0.1g

Chalfant Valley – Scaled to 0.1g

Excitation Frequency

Investigations into the effect of excitation frequency on the response behaviour of the pendulum model were conducted with sinusoidal excitations to evaluate the significance of resonance.

For any given pendulum system, the natural period (T), frequency (f) and angular frequency (ω) are related by Equation 1.

$$T_n = \frac{1}{f_n} = \frac{2\pi}{\omega_n} = 2\pi\sqrt{l/g} \tag{1}$$

Where *l* is the pendulum length in meters and *g* is the gravitational constant.

For the phenomenon of resonance to occur, the excitation frequency must be close to that of the

pendulum's natural frequency. A pendulum system with a mass of 5kg and wire length of 0.5m was used. This gives a natural period of $T_n = 1.42$s and natural frequency of $f_n = 0.71$Hz.

Concerning sinusoidal excitations, the acceleration, velocity and displacements induced can be described with the following relationships:

$$\begin{aligned} displacement &= A\sin(\omega t) \\ velocity &= A\omega\cos(\omega t) \\ acceleration &= -A\omega^2\sin(\omega t) \end{aligned} \tag{2}$$

Where A is the displacement amplitude in meters, ω is the excitation frequency in rads^{-1} and t is time in seconds.

From Equation 2, it is evident that the amplitude and hence displacement must vary to ensure the peak acceleration remains constant throughout the tests. The values used are shown in Table 2 and allow for the peak acceleration to remain constant at 0.1g.

Table 2. Shake-table input parameters

Required Excitation	Displacement (mm)	Frequency (Hz)
0.6 x f_n	139	0.42
0.8 x f_n	78	0.56
1.0 x f_n	50	0.71
1.2 x f_n	35	0.85
1.4 x f_n	26	0.99
1.6 x f_n	20	1.13

4 RESULTS & DISCUSSION

4.1 Analytical Results & Discussion

The relative displacement of the pendulum mass was obtained for each of the ground motions. This was then compared with the input displacement of the ground motion to determine the absolute displacement of the pendulum mass. The absolute displacement of pendulum mass was determined to be zero for each of the ground motions as the input displacement was equal and opposite to the relative displacement of the pendulum mass. This is illustrated in Figure 3 which shows a plot of the relative mass displacement and the input displacement from the ground motion.

The results of analytical modelling indicate that regardless of the excitation applied to the floor from which the ceiling is suspended, the ceiling will not experience any absolute movement. As suspected, this result was however, in contrary to the results from experimental tests with the shake-table, which are described in the following section.

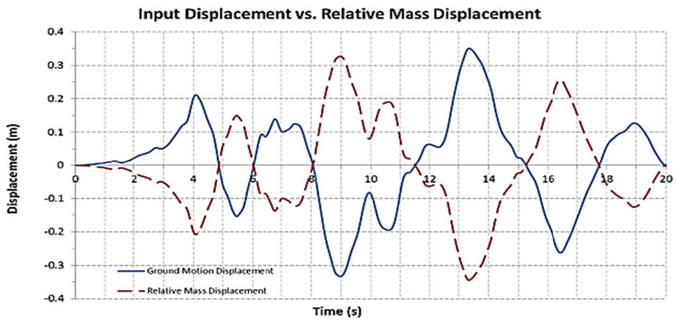

Figure 3. Input and relative mass displacement from analytical modelling in OpenSees

4.2 **Experimental Results & Discussion**

Effects of Mass: By varying the magnitudes of the suspended mass while keeping all other parameters constant, it was found that as mass increases, the maximum displacement of the pendulum also increases. Figure 4 below shows the resulting maximum displacements for each ground motion applied.

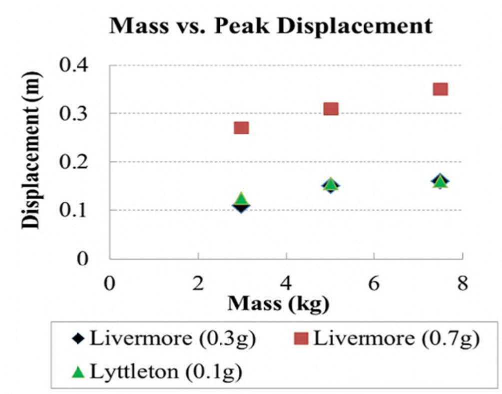

Figure 4. Maximum displacement response for the varying masses

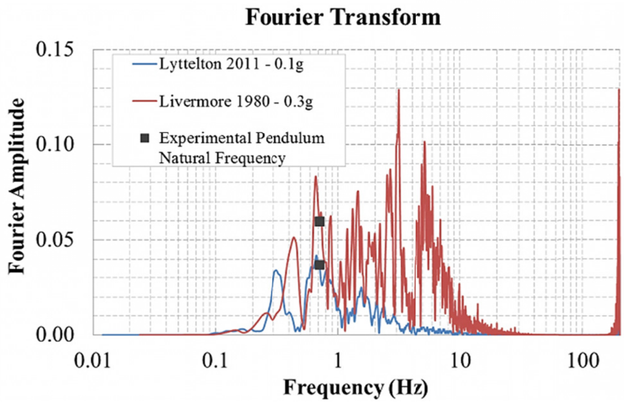

Figure 5. Fourier transforms for the Lyttelton 2011 and Livermore 1980 GMs

From the results plotted in Figure 4 the relationship between maximum displacement and mass appears to be non-linear in nature. The fact that the displacement increases with mass is unexpected however its effect on the peak displacement is relatively small. As such the influence of mass on the model's displacement response can be considered negligible.

The maximum displacements for the Lyttelton (0.1g) and Livermore (0.3g) ground motions are very similar as shown in Figure 4, despite having different peak accelerations. This can be explained by examining the Fourier transforms of each ground motion (Fig. 5). The Lyttelton ground motion (0.1g) has a smaller Fourier amplitude but the natural frequency of the pendulum is close to the middle of the dominant frequency range of the excitation. The Livermore ground motion (0.3g) on the other hand has a slightly higher Fourier amplitude but there is a wider dominant frequency range which reduces the effect of frequency resonance.

Concerning the effect of mass on the period of oscillation, it was found that varying mass did not affect the system's period of oscillation. Figure 6 shows the periods of oscillation both during the excitation as well as post-excitation for the mass values tested. It can be seen that the period stays at a somewhat constant value for each ground motion excitation induced. Thus it can be concluded that changes in mass had little effect on the natural frequency of the pendulum.

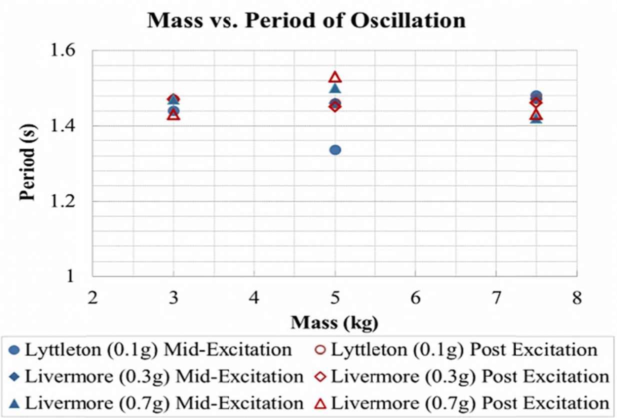

Figure 6. Comparison of mass and period for various GMs

Effects of Excitation Amplitude: By scaling the Livermore ground motion to various maximum

acceleration values and applying them to two pendulums of different masses, it was found that as excitation amplitude increased the resulting peak displacement response also increased. There is a strong positive correlation between these two parameters, and the trend appears to be linear (Fig.7).

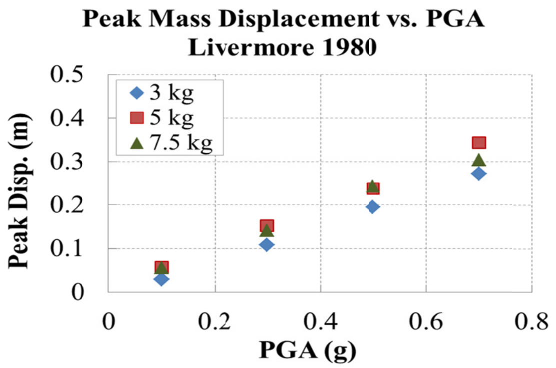

Figure 7. Effect of increasing Max excitation amplitude on the pendulum's Max displacement

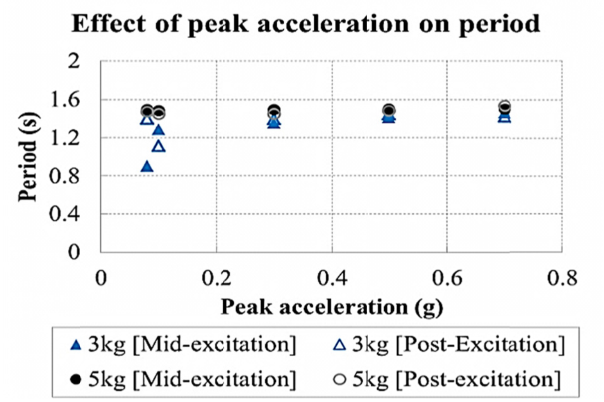

Figure 8. Observed oscillation periods for different Max acceleration.

The observed periods of oscillation for each excitation tested are shown in Figure 8. At low peak acceleration values, there seems to be considerable variations between observed periods of oscillation. This is especially the case for the 3kg mass, where the period is shorter. However, this variation could be the result of unidentified errors in experimental testing.

Effect of Pendulum Length: While keeping all pendulum parameters constant but varying the length, its effect on the pendulum's behaviour could be determined. Two ground motions were used to excite the model. These were chosen based on their Fourier transforms such that one had minimal amplification over the natural frequencies of the pendulums and the other such that it had significant amplification. Shown in Figure 9 are the maximum displacement responses as a function of pendulum length for each ground motion. It is worthwhile to note that the peak displacement obtained for the pendulum length of 0.8 m and Loma Prieta ground motion is considered to be an outlier as its magnitude cannot be explained. The Chalfant Valley displacement responses indicate a linear relationship, while the Loma Prieta ground motion appears to follow an almost bell shaped curve. However, excluding the 0.8m value for Loma Prieta ground motion, the dominant trend is increasing and linear.

Effects of Excitation Frequency

By applying sinusoidal excitations while keeping all other parameters constant, a plot of the frequency ratio and peak displacement response was obtained and shown in Figure 10.

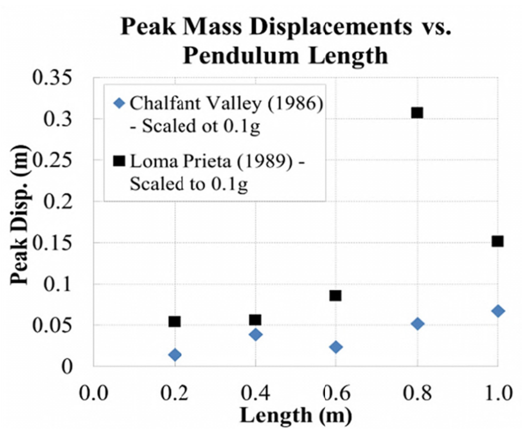

Figure 9. Maximum pendulum displacement responses for varying pendulum lengths

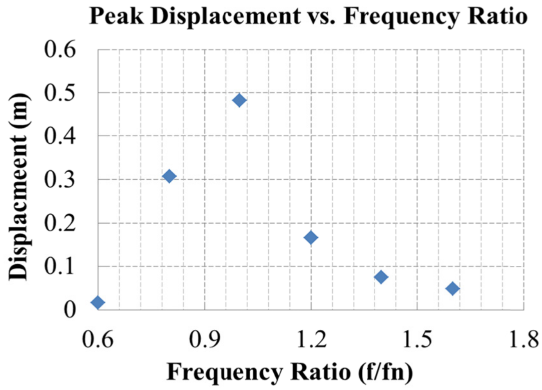

Figure 10. Peak displacement response for sinusoidal excitation with varying frequency ratios

The distribution of results in Figure 10 indicates an asymmetrical relationship when considering the distribution about a frequency ratio of 1.0.Firstly by examination of the peak displacements obtained from the frequency ratio range of 0.6 to 1.0, displacements seem to be increasing in a linear fashion with a steep gradient. A decreasing linear trend can be seen in the 1.2 to 1.6 frequency ratio range. However, there is a significant drop between values with a similar albeit negative slope. At this stage it is difficult to conclude the exact relationship between excitation frequency ratio and displacement response; however it is clear that the phenomena of resonance drastically amplifies the displacement response.

5 CONCLUSIONS

As the proposed floating ceiling design is essentially a uniform arrangement of multiple hangers, the results obtained from these preliminary investigations are to an extent, expected to apply to the full design.

The analytical modelling of a single ceiling hanger suggested the ceiling would remain in place with zero absolute displacement regardless of the excitations applied to the slab above. However, the experimental testing with a hydraulic shake-table demonstrated that this was not the case.

Based on the results presented, resonance has a strong influence on the peak displacement of the model. The effect of resonance is observed in ground motion excitation depending on the frequency content information provided by Fourier amplitude of the ground motion at the model's natural frequency.

The effect of mass on the response of the model was found to only be minor. Upon the increase of the suspended mass from 3 kg to 5 kg, only an average difference of 8 mm was observed. In addition the period of oscillation remained unaffected.

Upon increasing peak acceleration for a given ground motion excitation, a positive linear correlation with peak displacement response was observed. However this trend is not absolute as the peak displacement of the model was shown to be a function of both peak acceleration and frequency content.
To interpret what these outcomes mean to actual ceilings, a typical maximum hanging length of 0.5m is assumed so as not to impede on the available inter-storey height. The design response coefficient was calculated for a building in Christchurch, for which the resulting design response acceleration determined to meet serviceability requirements was 0.17g. By comparing this with the peak accelerations applied in the tests and the resulting peak displacements the approximate peak displacement to be expected from this would be no greater than 0.15m. This conclusion is only relevant to the case and conditions provided in this study. Further investigation into the effect of the modified motions from the structure is needed to make more firm conclusions. In the meantime and for the experiment presented, providing a gap of up to 0.15m around the ceiling's perimeter is within reasonable limits and hence it can be concluded that the concept of a fully floating ceiling system is feasible in meeting serviceability limit state requirements. It is proposed that the perimeter gap be covered by an architectural angle. In order to provide a degree of redundancy to the ceiling system an elastomeric strip can be affixed to the angle at the possible point of contact between the ceiling and wall. This would serve to dissipate energy and hence reduce potential damage should the displacement of the ceiling attempt to exceed that provided by the perimeter gap in severe earthquakes.

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