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FULLY-FLOATING SUSPENDED CEILING SYSTEM: EXPERIMENTAL EVALUATION OF THE EFFECT OF MASS AND ELASTIC ISOLATION

A. Pourali[1], R. P. Dhakal[2], G. A. MacRae[3], A. S. Tasligedik[4]

(1) PhD Candidate, University of Canterbury, Christchurch, New Zealand.

(2) Professor, University of Canterbury, Christchurch, New Zealand.

(3) Associate Professor, University of Canterbury, Christchurch, New Zealand.

(4) Research Engineer, University of Canterbury Quake Centre, Christchurch, New Zealand.

Abstract

This paper reports a full scale shake table testing of a fully-floating ceiling within a steel frame. The 2.15 m by 4.55 m ceiling is suspended from the floor above by vertical steel wires. A gap of 150mm is provided on all four sides of the ceiling. In the tests, ceilings of different masses were used with the surrounding gap packed with elastic acoustic isolation material. The frame is subjected to sinusoidal motions, and random table motions consisting of a range of frequencies and amplitudes. A satisfactory agreement between the fully floating ceiling response and simple pendulum theory was demonstrated with low acceleration and displacement response in the ceiling grid and tiles at excitation frequencies far from the ceiling's natural frequency of vibration. However, when subjected to input motions with frequencies close to the resonant frequency, the horizontal displacement of the ceiling exceeded the gap width resulting in large acceleration pulses due to the pounding action with the surrounding structure. The addition of an elastic perimeter isolation material was effective in decreasing the pounding impact and reducing the ceiling displacements and accelerations. The response of the test specimens was compared with the code requirements with respect to clearances. This comparison showed that the tested fully-floating ceiling had reduced ceiling displacements and accelerations as a result of the used ceiling isolation material. The only form of damage observed was a single panel dislodgement in one test.

Key words: frequency content, fully-floating ceiling, pounding, seismic response, shake table tests, perimeter isolation.

1. Introduction

Suspended ceilings serve a wide range of purposes in a building, including sound and fire protection, aesthetic benefits and a safe and clean finish over the engineering systems and services in plenum space. Consequently, the uninterrupted performance of these components is necessary for the occupancy of buildings after an earthquake. Damage to suspended ceilings has proven to cause significant financial loss in the form of direct damage [1, 2] as well as downtime [3]. In certain cases, damaged ceilings can also pose a risk to the lives of building occupants [4, 5]. In order to mitigate the risks associated with the failure of ceiling systems, there are two approaches that can be followed: i) Identifying the ceiling weaknesses and carrying out a detailed design of the ceiling; ii) Minimizing the imposed demand to the ceiling system. A fully-floating ceiling, as opposed to a perimeter-fixed or braced ceiling, is a system with no stiff lateral restraints to the supporting structure. The ceiling is hung from the floor via vertical steel hanger wires and is provided with gaps on perimeters. Given sufficient gaps to accommodate the deflections resulting from earthquakes, minimal contact among the edges of the ceiling and the perimeter walls is expected. As a result, there can be very low interaction with the walls and the ceiling damage may be reduced. The simple pendulum theory forms the basis of the fully-floating ceiling system presented in this study. As in all pendulum problems, the main issue associated with this concept is the phenomenon of resonance. Should the frequency of an excitation be close enough to that of the pendulum's natural frequency, then displacement amplification is to be expected. Uncontrollable displacements in a fully-floating ceiling may result in undesirable interactions with other services within the plenum space. Therefore, perimeter isolations were proposed as a possible method of limiting ceiling displacements.

A simple gravity pendulum is a weight hanging from a frictionless pivot point through a massless rod. This idealized frictionless system swings at a constant amplitude with a period that mainly depends on the length of the pendulum (L) and the acceleration due to gravity. Equation (1) shows this interrelation.

$$T = 2\pi\sqrt{\frac{L}{g}} \tag{1}$$

Past research showed that in comparison to the ceilings supported by 45-degree splay wires, the pendulum ceilings have lower peak acceleration whilst having higher peak displacement [6]. In another study, the shake table testing of fully floating (or pendulum) ceiling systems used in Taiwan [8] showed that the period of these ceilings could be calculated by pendulum theory accurately. Moreover, the results suggested that the ceiling performance was sensitive to the use of transverse cross tees on edges [7]. In a preliminary study carried out at University of Canterbury [9], the feasibility of a ceiling that performs as a simple pendulum was investigated. The numerical and experimental study showed that: i) The length of the rod controls the natural frequency of the pendulum as well as its sensitivity to a particular motion, ii) The mass has a negligible effect on pendulum peak displacement and does not change the natural frequency, iii) Displacement amplifications were observed at resonance frequencies of the input motion, and iv) Displacement amplifications were observed also at higher input acceleration amplitudes.

The limited extent of the experimental work mentioned reveals the need for more extensive study into the characteristics of a pendulum ceiling and its practicality. The reported research aims at addressing the following:

1) Comparison of fully-floating ceiling response with the response of a pendulum
2) Displacement levels in a fully floating ceiling under a particular motion
3) Effect of ceiling mass on fully floating ceiling response
4) Ceiling acceleration amplifications compared to the floor acceleration
5) Effect of elastic isolation material as confinement around the perimeter of the fully floating ceiling.
6) The efficiency and effectiveness of the tested ceiling typologies for practical applications.

2. Design of the experiment

2.1 Test specimen

The size of the ceiling specimen was 2.15 m × 4.55 m (Figure 1). The steel wires used to hang the ceiling were made up of 12-gauge galvanized, 450 mm long soft annealed mild steel [10]. The ceiling consisted of DONN brand standard main tees and cross tees. The ceiling tiles were 1200 mm × 600 mm, which are the typical tiles used in NZ [11, 12]. The fully floating ceiling was not attached to the perimeter walls/beam on any side. Therefore, to maintain the integrity of the system, DONN brand US45 channels were used on all four sides of the ceiling. These channels were connected to the tee ends via 3.2 mm aluminium rivets. For ease of installation, standard MT45 or MT55 angles are recommended instead of channels [11,12]. Three configurations of this specimen were tested with variations in ceiling weight and perimeter isolators (Table 1). The perimeter isolation material was an industrial foam (Dunlop Foams™) with hardness and density values of 70 N and 16 kg/m^3, respectively. Here, hardness (load bearing) is a measure of the 'feel' of a foam, which is established by compressing a standard size piece of the foam to 40% of its thickness using a cylindrical apparatus of approximately 200 mm diameter and measuring the force (expressed in Newtons) required to achieve this. ASTM D3574 – 11 [13] lays out the details and test method for acquiring the measure of hardness of foams in Test B1, Indentation Force Deflection (IFD) Test.

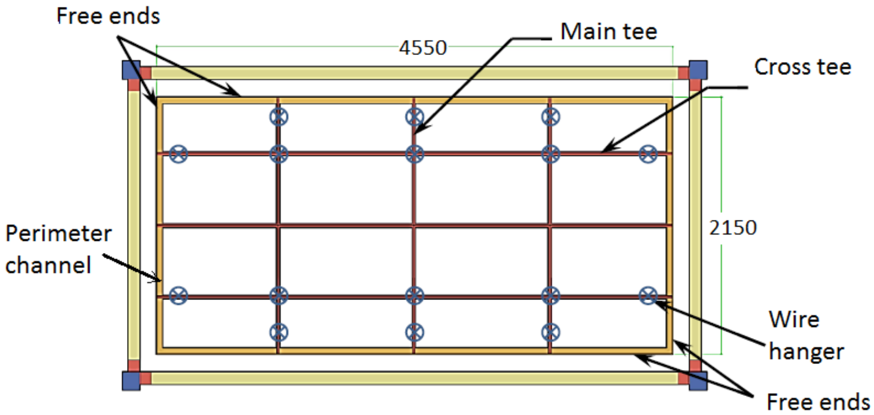


Figure 1 – Plan view of fully-floating ceiling specimen

Table 1: Details of specimens.

No.	Symbol	Total mass (kg)	Perimeter Isolation
1	WPA	37.4	No
2	Add. mass	59.4	No
3	Foam	37.4	Yes

Notation: WPA: Hanger layout A, Add. Mass: Hanger layout A with additional mass, and Foam: Foam isolated.

2.2 Test setup and instrumentation

The setup was constructed on a 2 m by 4 m unidirectional shake table. The frame (Figure 2) was 5.20 m long, 2.65 m wide and 2.8 m high, which could accommodate a 2.15 m by 4.55 m ceiling. The frame used in this study was relatively rigid with a horizontal frequency of 12.5 Hz in the direction of excitation (E-W). This ensured that the excitation input to the table was close to that of the ceiling supports (i.e. the acceleration response of the frame).

A total of 12 accelerometers and 3 potentiometers were used for recording the test outputs in these tests (Table 2). The location of these instruments is shown in Figure 2. In addition to these devices a high speed video camera was also situated underneath the ceiling on the west end of the test specimen. The recordings from this camera were digitised and analysed using the Hedrick tracking software [14] in MATLAB to derive the displacement of the ceiling.

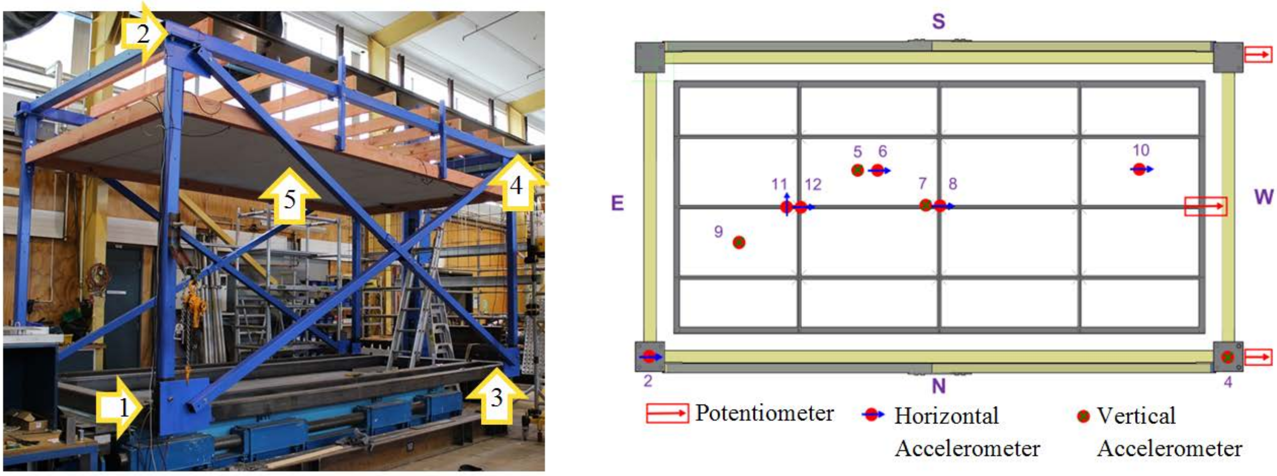


Figure 2 – Instruments on test frame and test specimen

Table 2 - List of accelerometers

No.	Location	No.	Location	No.	Location
1	Shake table input (Hrz.)	5	Central tile (Vrt.)	9	Perimeter tile (Vrt.)
2	Frame top (Hrz.)	6	Central tile (Hrz.)	10	Perimeter tile (Hrz.)
3	Shake table input (Vrt.)	7	Central grid (Vrt.)	11	Grid (NS)
4	Frame top (Vrt.)	8	Central grid (Hrz.)	12	Grid (EW)

2.3 Test input motion

A series of sinusoidal motions with different displacement amplitudes and frequencies was chosen for the initial tests. Each sinusoidal wave included a short ramp phase at the start and at the end. The motion between these two ramps continued with constant displacement amplitude and frequency for approximately 15 s. Figure 3 shows the range of peak floor accelerations (PFAs) achieved at the ceiling support level (i.e. at the top of the frame) for different frequencies along with the acceleration recorded on the shake table. Following these sinusoidal tests, a suite of ground motions, chosen such that a wide range of frequency content could be covered, was used as the input. The record amplitudes were scaled according to the limitations of the shake table and the objective of the tests.

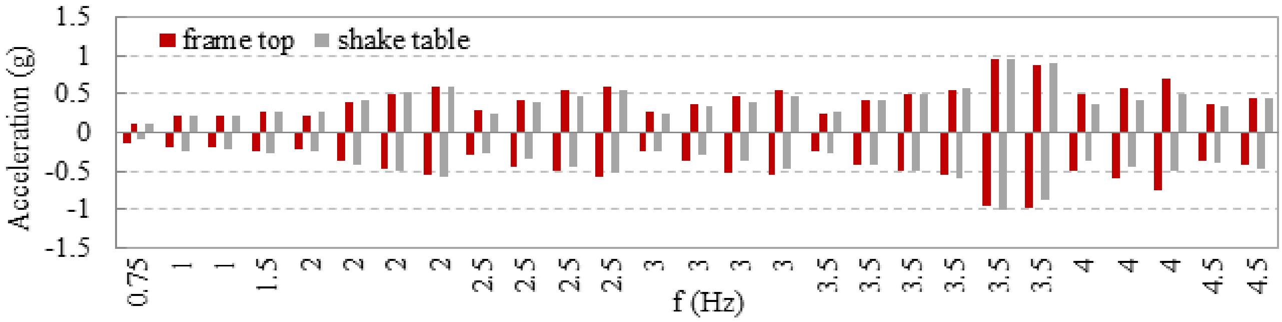


Figure 3 – Acceleration recorded on shake table and acceleration response on frame top

3. Results and discussions

3.1 Natural properties of the specimen

Considering the dimensions of the ceiling and the pendulum theory (Equation 1), the period of the ceiling was approximately 1.34 s. Values of natural frequency and damping ratio of the ceiling specimens were measured using the free vibration phase of experiments and/or transfer function. The results obtained are summarized in Table 3.

Table 3 – Natural frequencies and damping ratios obtained from ceiling

Test description	Average natural frequency [Hz]	Average damping ratio
Fully-floating ceiling – Hanger A	0.774	0.012
Fully-floating ceiling with additional mass	0.751	0.0074

As it can be seen in Table 3, the fundamental frequency of the ceiling specimen was independent of the mass of the ceiling. The measured frequency was close to the natural frequency calculated based on Equation (1), which was 0.74 Hz for a pendulum length of 450 mm. However, 38% decrease was recorded in the damping ratio when the total mass of the ceiling was increased by 59% (22 kg). Such a reduction is expected based on the relation between damping ratio and mass ($\xi = \dfrac{c}{2m\omega_n}$).

3.2 Ceiling displacement range

3.2.1 Effect of magnitude and frequency of sinusoidal motion

In a fully-floating ceiling, the ceiling displacements should remain small to prevent pounding against surrounding walls. Since majority of the used sine waves were at frequencies higher than the natural frequency of the pendulum ceiling, the ceiling was relatively stationary or moved very little throughout most of the tests. Values of ceiling absolute displacement remained below 5 mm in all tests with input motion frequency of 2 Hz and higher (Figure 4a). As the frequency of the input sine wave approached the natural frequency of the specimens i.e. 0.77 Hz, an increase in displacement was generally observed as shown in Figure 4b & 4d. At excitation frequency of 0.75 Hz pounding occurred as a result of relative displacement exceeding the perimeter gap (150 mm). A slight increase in peak ceiling displacement was noticed when higher amplitudes of accelerations were applied using the same input frequency (Figure 4c & 4d). However, response of the pendulum ceiling was more influenced by the frequency of the motion rather than the acceleration amplitude. In none of the sinusoidal tests without foam and carried out at an excitation frequency of 1 Hz to 4.5 Hz pounding occurred. However, relatively large displacements were measured at 1Hz (63.9 mm) even at low floor accelerations (Figure 4d).

3.2.2 Effect of foam on all ground motion records

In experiments with perimeter isolation foam, due to installation limits, the gap was reduced to 100 mm which was fully filled with foam. When the specimens were tested using recorded earthquake ground motions, the resulting displacements were generally larger than the sinusoidal motions and the results were significantly affected by the frequency content of the applied acceleration time histories (Figure 5). The values of peak displacement in tests under earthquake ground motion with isolation foam were consistently smaller than similar tests without isolation foam. This will be further discussed in Section 3.4.

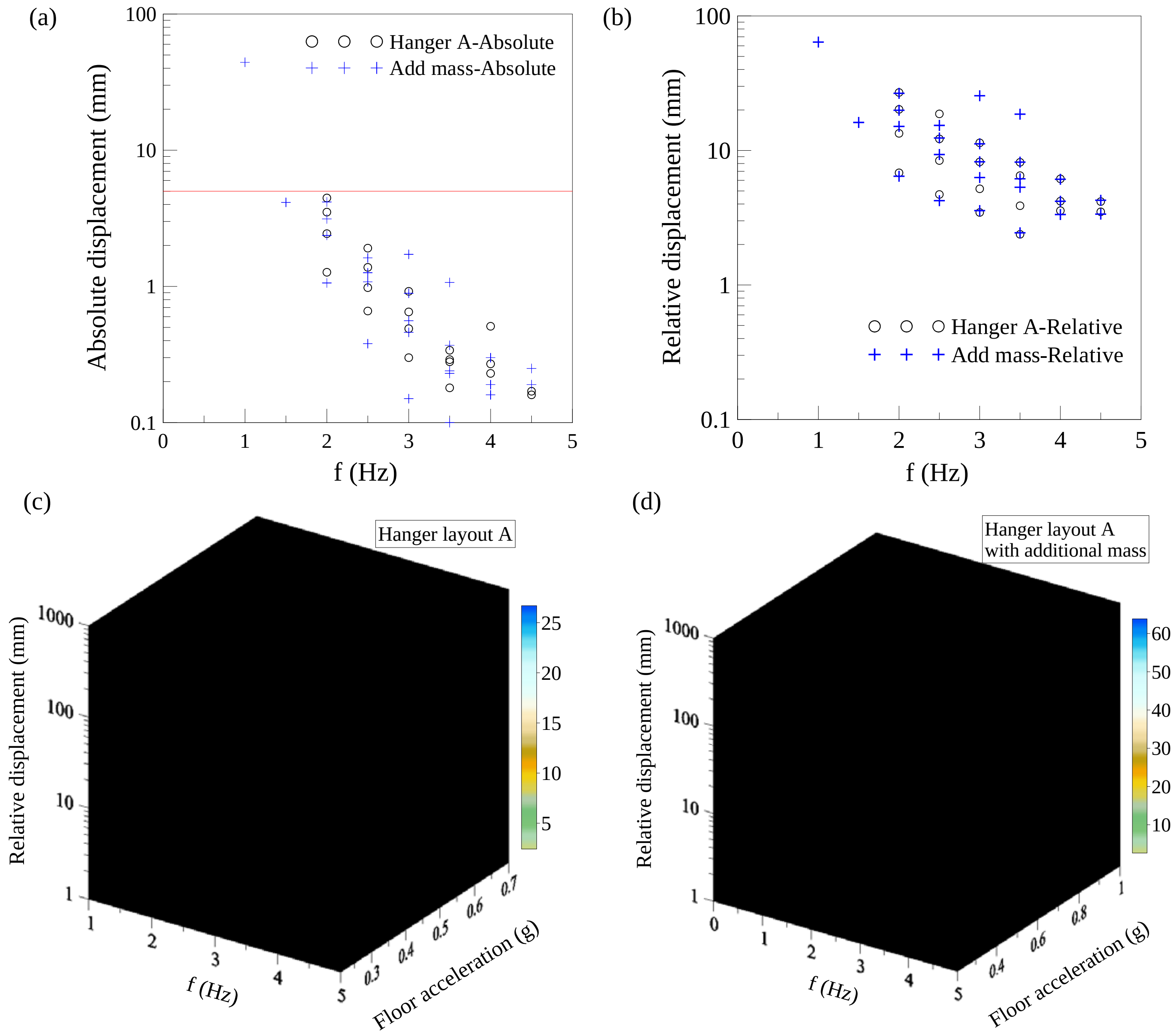


Figure 4 - Ceiling peak displacement in sinusoidal tests

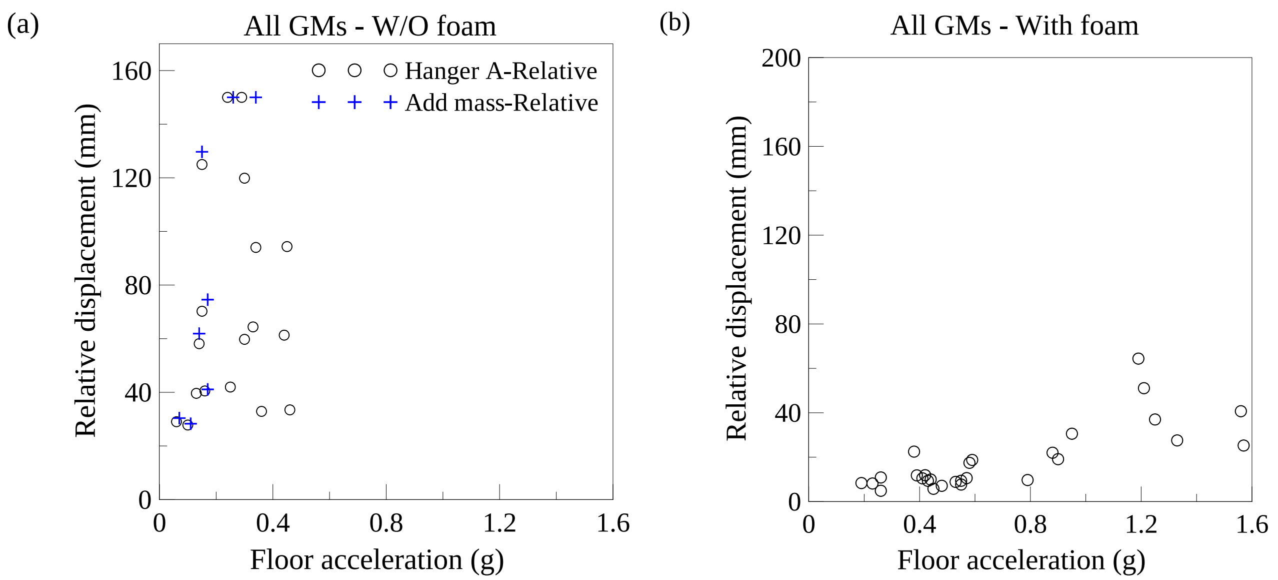
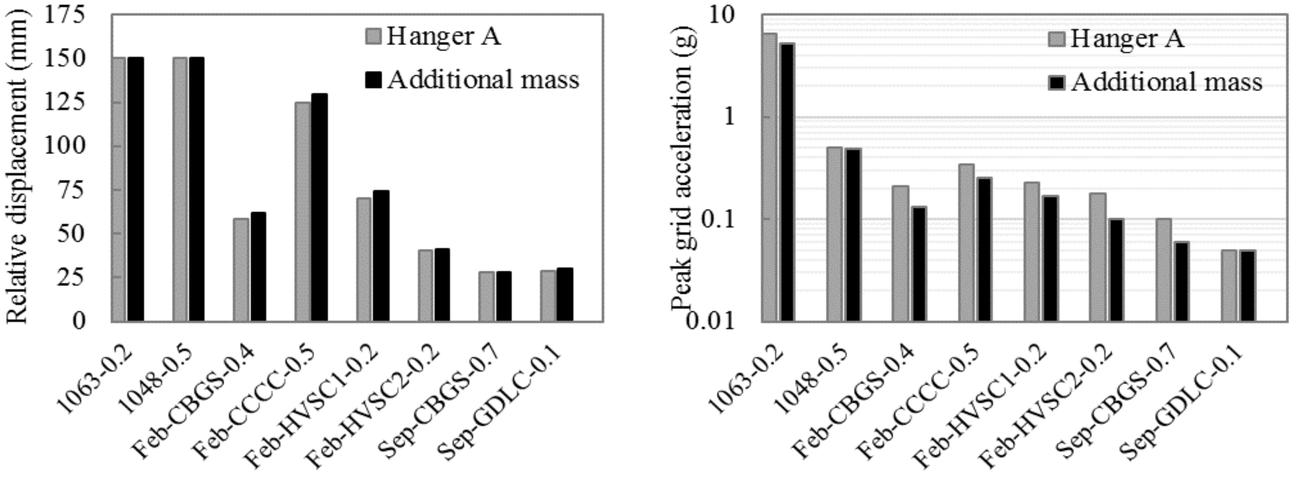


Figure 5 - Ceiling peak displacement in ground motion tests

3.3 Ceiling weight

As discussed in Section 3.1, increasing the mass of the ceiling by 22 kg (59%) did not have a significant effect on the natural frequency of the system. On the other hand, it caused a reduction in the damping ratio of the ceiling system. Comparing values of peak displacement in ground motion tests show either similar or slightly increased values for the heavier specimen (Figure 6a). These differences vary between 1-6 millimetres (0.5 to 6.5 percent of the total displacement). Since all displacement data in these tests are derived from digitised videos the results are accurate enough, but not exact. In addition to the displacements, the peak horizontal accelerations recorded at the centre of the ceiling grid are also compared in Figure 6b. For the heavier ceiling, majority of the recorded accelerations were smaller than that for the lighter ceiling.



(a) (b)

Figure 6 - (a) Peak ceiling relative displacement, and (b) grid acceleration in ground motion tests

Similar comparisons were made for the displacement measurements taken in sinusoidal tests (Figure 7). As it can be seen, the differences in displacement are negligibly small. Similarly, the peak grid acceleration values are smaller in the heavier specimen (Figure 8). These results indicate that the idea of a pendulum ceiling is feasible even considering heavy ceilings with services and lights attached, as the response of the ceiling was not significantly affected by the increased mass. However, since pounding is probable, any attached luminaries and services need to be positively secured and sufficient clearance needs to be provided.

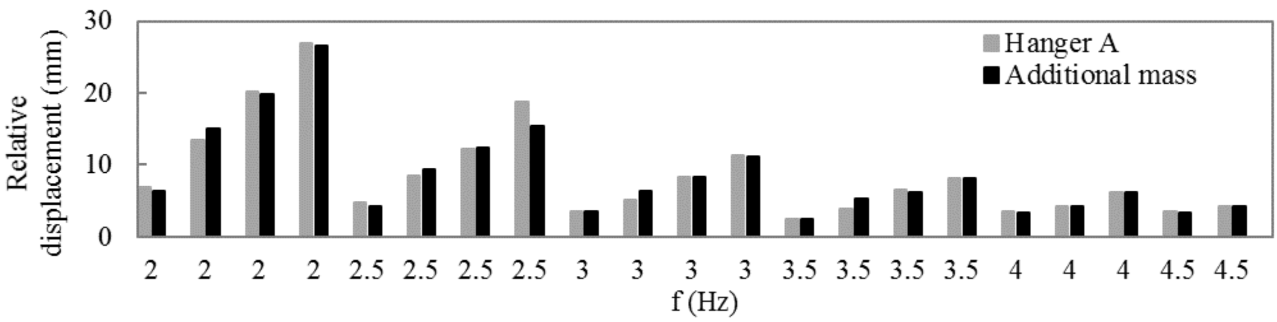


Figure 7 - Peak relative displacement in sinusoidal tests, hanger layout “A” with and w/o added mass

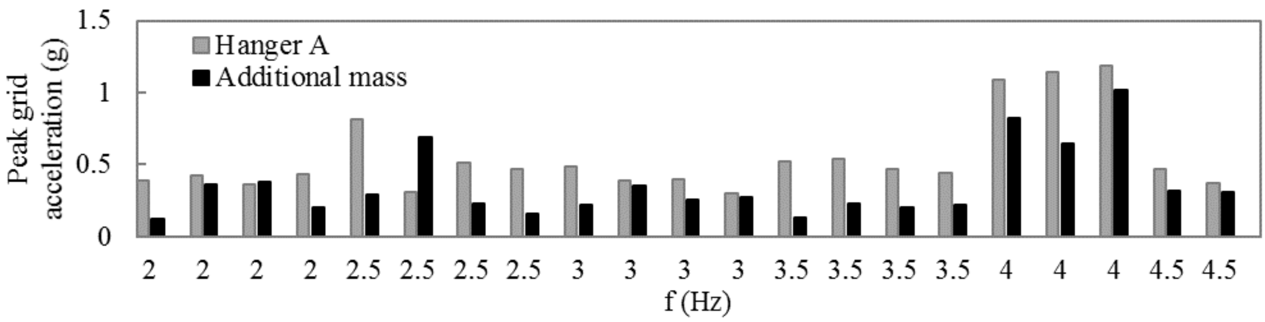


Figure 8 - Peak grid acceleration at ceiling centre, hanger layout A, with and w/o added mass

Due to difficulties of installation and limited time, instead of using heavy tiles, small sand bags were evenly distributed over the ceiling grid (Figure 9). Ceiling tiles are in general loosely fitted in grid modules with a minimum gap of 5 mm in each direction and were observed to vibrate in vertical and horizontal directions during tests. The placement of these masses (i.e. sand bags) limited the overall vibration and sliding of the tiles.

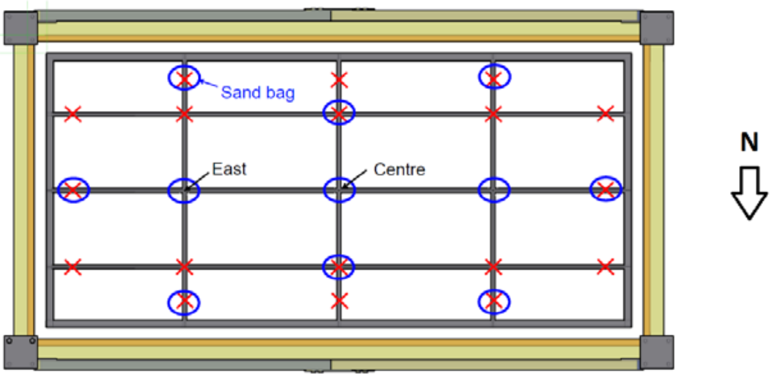


Figure 9 - Plan view of specimen with hanger layout A, position of sand bags and centre and east grid joints

Figure 10 shows two sets of acceleration time histories corresponding to two similar sinusoidal tests with the frequency and displacement amplitudes of 2.5 Hz and 4 mm, respectively. The graph shows accelerations recorded on the specimen without (Figure 10a & 10c) and then with the additional mass (Figure 10b & 10d). To measure the acceleration response of the ceiling, accelerometers were placed in horizontal direction on grids at the centre and east locations of the ceiling (Figure 9). Compared to the rest of the tiles, the tiles placed around the central joint were more restrained by sand bags. This resulted in smaller acceleration values at this location. Also, the recorded response acceleration time history had a more even distribution with rare spikes in the response. Similar behaviour was observed in other sinusoidal and ground motion tests. These observed large accelerations on the ceiling grids might have been caused by the sliding movement of tiles, which results in impact between tiles and grids. Since these impacts occur at very short periods of time, their effect was expected to be less destructive than the acceleration induced by the structure. This effect in restraining tiles' movement can be replicated through use of ceiling retainer clips in practice. A study by Badillo-Almaraz et al. [15] showed that using retainer clips substantially improved the performance of the suspended ceiling systems by preventing tiles dislodgement failure.

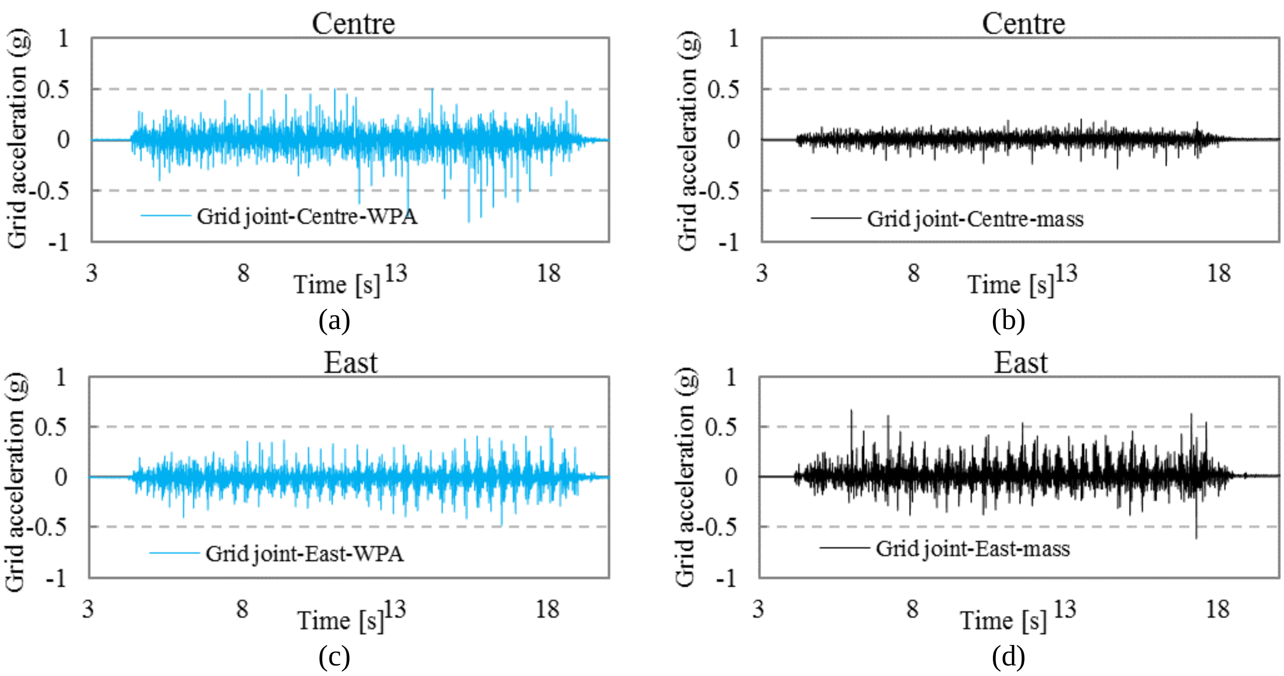


Figure 10 - Horizontal acceleration time histories on ceiling grid in sinusoidal tests (a & c) with and, (b & d) w/o added mass

3.4 Effect of perimeter isolation

In the final set of tests, the gap on ceiling perimeters was filled with acoustic isolation foam (Figure 11). This material is flexible and allows the ceiling to dampen the movements and pounding impact. The behaviour of this material was tested under sinusoidal loading (SW) and earthquake ground motion (GM).

Figure 11 - Isolation foam placed in and filling the perimeter gap

The displacement values observed in all the tests with isolation foam showed that the displacements in sinusoidal and earthquake ground motion tests were less than 20 mm, in 78% of the sinusoidal cases and in 68% of the GM cases (Figure 12c & 12d). Whereas in tests under earthquake ground motion (GM) without isolation foam, all the recorded displacements were above 20 mm (Figure 12a). When comparing similar specimens with and without isolation foam, it was observed that in all tests with earthquake ground motions (GM), using isolation foam effectively decreased the displacements of the ceiling (Figure 13a). In foam isolated tests, larger displacements mainly coincided with larger floor acceleration (Figure 12c).

Figure 13b shows the effect of isolation foam on the recorded accelerations at the centre joint of the ceiling. As it can be seen in Figure 14a, the peak displacements were approximately 100 mm for the ceiling specimens without any perimeter isolation foam. Installation of perimeter isolation foam, which acts as a dissipator, reduced these peak displacements significantly, which is approximately 5-8 mm. Moreover, considering the ceiling grid acceleration measurements shown in Figure 13b, the perimeter isolation foams reduced the ceiling accelerations to a lesser extent. In this case, the observed acceleration reductions were not as consistent as the achieved displacement reductions. This can be due to the fact that the only dissipation given by these isolation foams are based on their hysteretic response (i.e. only a spring system). Consistent acceleration reductions may be achieved if viscous based damper materials/elements are included within the foam itself (i.e. a dashpot). The other contributing factor is the impact between the ceiling and the foam surface as the two surfaces were not joined or glued.

The sinusoidal tests of the ceilings without isolation foam showed that the recorded absolute displacements were generally small since the input motion frequencies were larger than the natural frequency of the ceiling. On the other hand, when isolation foam was present in the perimeter, the movement of the test frame interacts with the movement of the ceiling. Consequently, larger displacements were measured above sinusoidal input motions with a frequency of 3Hz. However, as the sine waves approached the natural frequency of the pendulum ceiling without foam (0.77 Hz), similar to tests under earthquake ground motion, the foam proved effective in limiting the displacement (Figure 14).

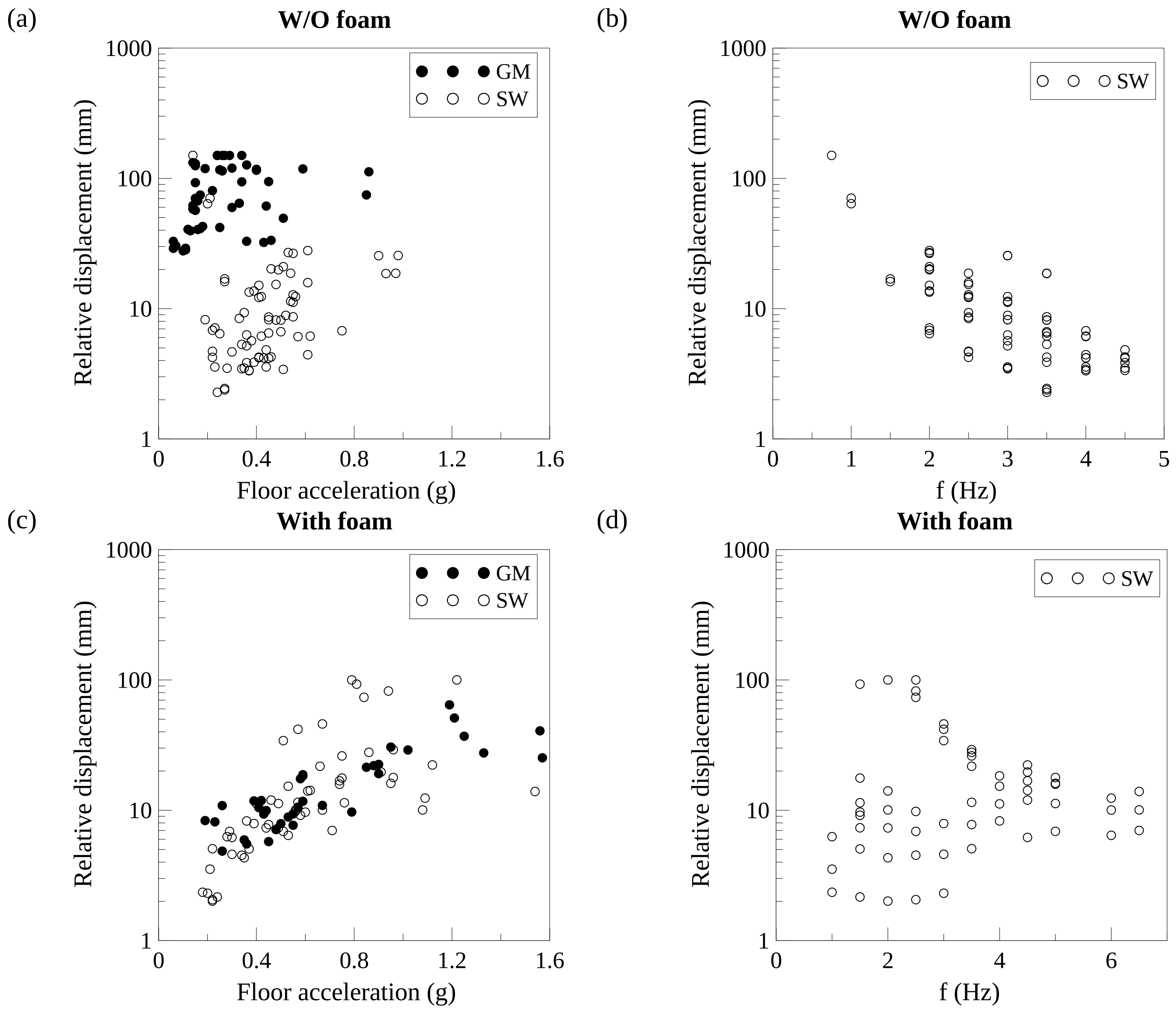


Figure 12 - Peak ceiling relative displacement in sinusoidal (SW) and ground motion (GM) tests w/ & w/o foam

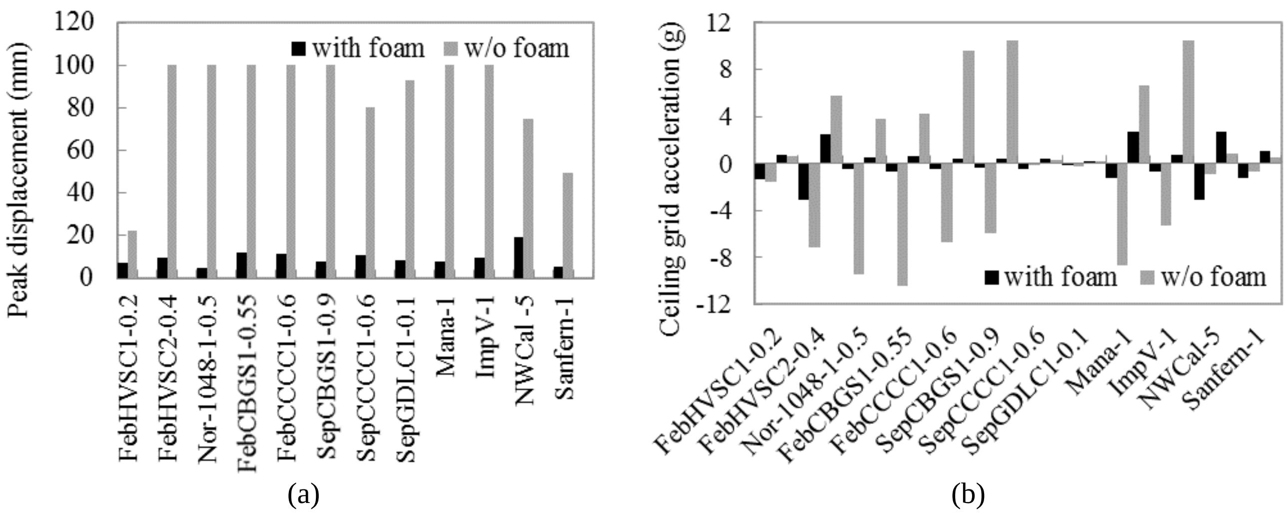


Figure 13 - (a) Peak ceiling displacement; and (b) acceleration on central grid joint w/ & w/o foam

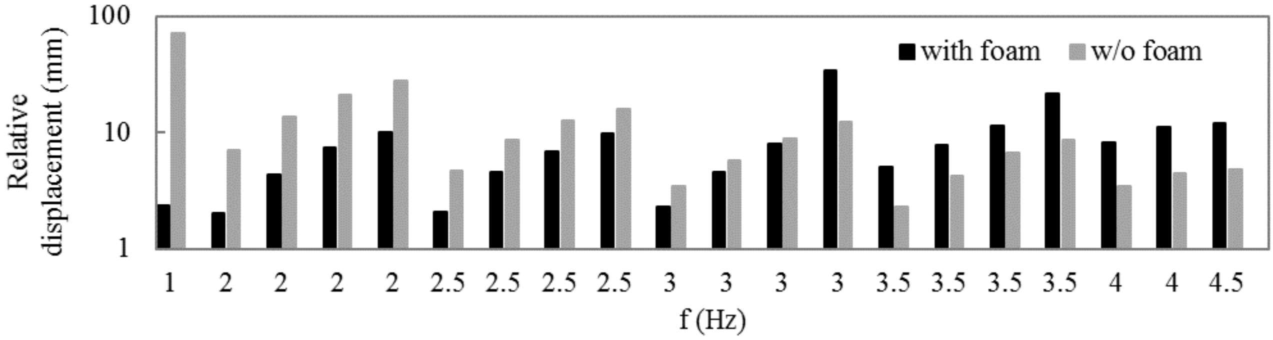


Figure 14 - Peak ceiling displacement with and without foam isolation in sinusoidal tests.

Figure 15 shows the cumulative distributions of the peak relative displacements in all tests carried out on ceilings with and without isolation foam. The effect of isolation foam was especially noticeable in tests with ground motion records and without foam as these tests generated large displacements from the ceiling (due to the wide range of frequencies in a ground motion).

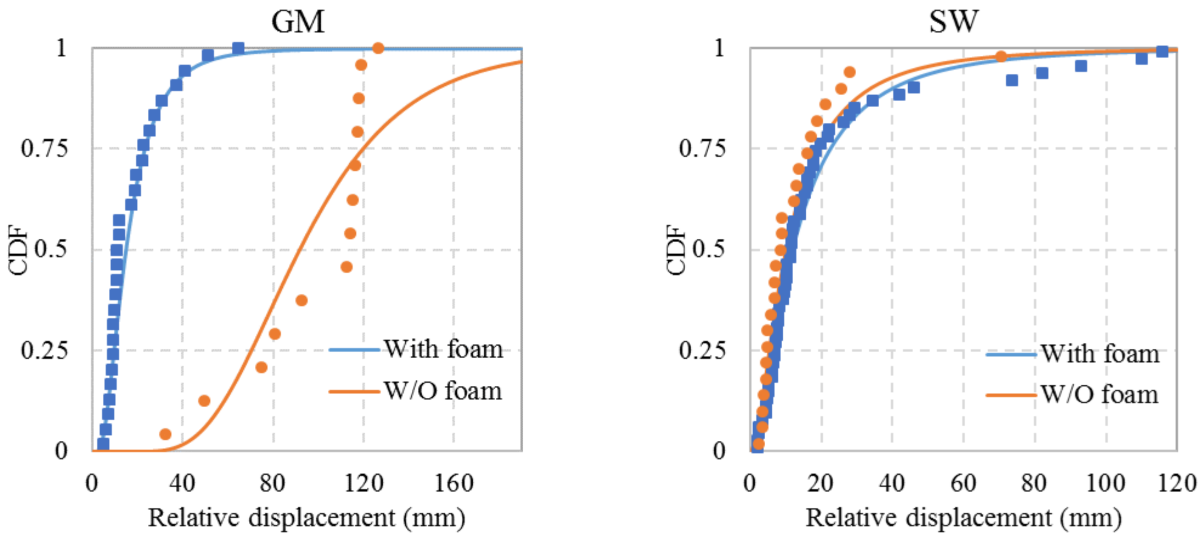


Figure 15 - Distribution of ceiling peak relative displacement in ground motion (GM) and sinusoidal (SW) tests, with and without isolation foam

3.5 Damage observations

Throughout more than 230 tests run on the specimen in various configurations, no damage was observed in the ceiling grid system. The only mode of failure observed was in the final sinusoidal test in the form of panel dislodgment (Figure 16). This happened due to pounding against perimeter beams coinciding with large vertical acceleration in the ceiling centre. The values of horizontal acceleration recorded on the shake table, at the top of the frame and ceiling grid were 1.14g, 1.22g and >10g (impact due to pounding), respectively. The test was stopped as soon as the panel dislodgment occurred.

3.6 Applications and implications

A suspended ceiling in general application is not an isolated element. They may interact with other non-structural elements and occasionally provide support for parts such as luminaries, partitions and building services. According to NZS4219:2009 [16], the seismic performance of the ceiling must be compatible with these elements. Similar to the requirement of current suspended ceilings, partitions need to be separately braced to the upper floor. The design of the partitions also needs to account for the pounding from ceilings. The fully-floating ceiling itself has a framing component connected to all terminal grid ends. Therefore, the integrity of the ceiling system is not dependent on any surrounding elements.

A fully-floating ceiling is a displacement-sensitive component rather than acceleration- sensitive, which makes the provision of sufficient clearances a crucial element in design. Table 4 shows the minimum clearances required according to Clause 5.2 of NZS4219:2009 [16]. Unlike current suspended ceilings, a pendulum ceiling is considered an unrestrained component. Accordingly, the clearances mentioned in Table

4 must be maintained between all ceiling components and other restrained or unrestrained elements. For example, the clearance between the pendulum ceiling and a restrained partition wall needs to be a minimum of 150 mm. Any objects penetrating through the ceiling (e.g. fire sprinklers) need to have 25 mm clearance all around [16]. Such penetrating objects need to be provided with flexible joints if used with a pendulum ceiling. As advised in Clause 5.2.2 [16], the use of flexible connections, such as perimeter isolation foam can reduce the required clearance amount. Further investigation is recommended in order to clarify the relation between the mechanical properties of the isolation material and the required size of the clearance.

Figure 16 - Panel dislodgment in the final sinusoidal test

Table 4 – Clearances [16]

Condition being considered	Minimum clearance (mm)	
	Horizontal	Vertical
Unrestrained component to unrestrained component	250	50
Unrestrained component to restrained component	150	50

The horizontal acceleration coefficient for ceilings can be calculated according to NZS 1170.5:2004 [17] serviceability and ultimate limit states (SLS & ULS). For example, this coefficient for a ceiling located in Christchurch, NZ equals 0.6 as shown in Equations (2) and (3). In these Equations: Seismic zone factor Z = 0.3, near-fault factor N (T, D) =1, spectral shape factor for soil type C at zero second period $C_h(0)$ = 1.33, return period factor for SLS design R = 0.25, floor height coefficient C_{Hi} = 3 and part spectral shape factor $C_i(T_p)$ = 2.

$$C(0) = C_h(0) \cdot Z \cdot R \cdot N(T,D) = 1.33 \times 0.3 \times 0.25 \times 1 = 0.1 \tag{2}$$

$$C_p(T_p) = C(0) \cdot C_{Hi} \cdot C_i(T_p) = 0.1 \times 3 \times 2 = 0.6 \tag{3}$$

According to Figure 12c, up to the floor acceleration of 0.3g in SLS (excluding the factor of $C_i(T_p)$ = 2 in Equation (3)), in none of 13 tests the peak relative displacement exceeded 25 mm. If considering ULS horizontal acceleration coefficient which is 4 times the SLS (i.e. 1.2g), in total of 86 tests 13 exceeded 25 mm displacement. In other words, in sinusoidal and ground motion tests altogether, 100% of the tests subjected to SLS and 85% of tests subjected to ULS level acceleration, the displacements remained below 25 mm. In one of the tests up to 1.2g floor acceleration pounding occurred as the relative displacement reached the 100 mm gap length. This indicates that in terms of clearances and damage to grid system, the fully-floating ceiling tested with the flexible isolation material provided had a satisfactory performance in an SLS event. When subjected to a ULS event, modifications may be required in terms of the stiffness of the isolation material used to remain within the limits of required clearances.

4. Conclusions

A pendulum-type fully-floating ceiling has been tested on shake table using sinusoidal and earthquake input motions. The test results were consistent with the simple pendulum theory. The natural frequency and the peak displacement of the fully-floating ceiling was independent of the ceiling total mass. Larger displacements were recorded at input frequencies close to the natural frequency of the ceiling. Increased ceiling mass limited the vibrations and sliding observed in ceiling tiles.

The isolation foam was effective in reducing the ceiling displacement and acceleration. The tests carried out using earthquake ground motions resulted in consistently smaller peak displacement values when compared to the same tests carried out for the ceilings without these foams. 78% of the sinusoidal tests and 68% of the earthquake ground motion tests showed peak ceiling displacements less than 20 mm whilst larger displacements among them were associated with larger floor accelerations. Throughout the tests damage was only observed in a sinusoidal test as panel dislodgement. The panel failure was assumed to be caused by impacts and the large ceiling accelerations. No grid failure was observed during these experiments.

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