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Fully-Floating Suspended Ceiling System: Experimental Evaluation of Structural Feasibility & Challenges

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ABSTRACT: Following preliminary experiments on the feasibility of a fully floating (like a pendulum) ceiling concept, full scale shake table tests are carried out on fully-floating ceiling specimens on an earthquake simulator in the University of Canterbury. The experiments are carried out to evaluate the seismic response of a 2.1m by 4.5m fully-floating ceiling that is isolated from the structure around and hung from the floor above via steel wires with no lateral resistance. A gap of 150mm is provided on all four sides of the ceiling. The specimens are subjected to two types of input motion: earthquakes and sine waves. The inspected parameters in these tests are: frequency content of the input motion, excitation amplitude, position of wire hangers, and ceiling weight. Results show a satisfactory agreement with the pendulum concept. The ceiling shows minimal displacement and excitation at frequencies far from its natural frequency. At this stage small accelerations were induced in the suspension system and tiles. However, when subjected to intense input motions at resonance frequencies, the swing of the ceiling was greater than the 150mm gap and large acceleration pulses were recorded in the system due to pounding with the surrounding structure.

1 INTRODUCTION

Suspended ceilings serve a wide range of purposes in a building, including sound and fire protection, aesthetic benefits, 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 inhabitability of buildings after an earthquake. Damage to suspended ceilings has proven to cause significant financial loss in the form of direct damage (Dhakal 2010, MacRae et al. 2012) as well as downtime (Ferner et al. 2014). This form of damage can also pose a risk to the lives of building occupants (Motosakaa and Mitsujib 2012 & Nation Media, 2011). One approach towards prevention of such losses is to identify the capacity and weaknesses of the system and attempt to strengthen it. Another approach can involve minimising the demands transmitted to the system. In case of suspended ceilings, which are sensitive to acceleration, one solution is isolating the ceilings from the structural components that transmit acceleration i.e. walls and floors by eliminating the stiff connections between the structural components and the suspended ceiling. 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 above via vertical steel hanger wires and is provided with gaps on perimeters. Provided that these gaps are sufficient to accommodate the deflections resulting from earthquakes, there should be no/minimal contact between the ceiling edge and perimeter walls. As a result, there can be no interaction with the walls and ultimately no damage should occur in the ceiling or perimeter walls. 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.

A simple gravity pendulum is a weight hanging from a frictionless pivot point through a massless rod or cord. This idealized frictionless system swings at a constant amplitude with a period that mainly depends on the length of the pendulum and the acceleration due to gravity. Equation 1 below shows this interrelation. In reality however, pendulums are subject to friction and air drag which gradually reduces their amplitude of oscillation.

$$T = 2\pi\sqrt{\frac{L}{g}} \qquad (1)$$

The equation of motion for a simple frictionless pendulum with a swinging mass of *m* and length of *l* can be derived through the method of energy (Figure 1):

$$E = K + U = \frac{1}{2}mv_\theta^2 + mgl(1-\cos\theta) = \frac{1}{2}m\left(l\frac{d\theta}{dt}\right)^2 + mgl(1-\cos\theta) \qquad (2)$$

Through differentiating E with respect to t:

$$ml^2\ddot{\theta} + mgl\sin\theta = 0 \qquad (3)$$

$$\ddot{\theta} + {}^{g}\!/_{l}\,\theta = \ddot{\theta} + \omega^2\theta = 0 \qquad \text{(for small rotations } sin\theta \approx \theta\text{)} \qquad (4)$$

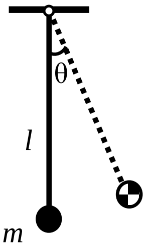

Figure 1 – simple pendulum

The solution for this equation can be in the form of $\theta = \theta_{\max}\sin\omega t$. Consequently, the displacement, velocity and acceleration of a pendulum are independent of its mass. These parameters are only affected by the pendulum's change of natural frequency which depends on the pendulum length and gravity acceleration.

One of the earliest studies on suspended ceilings (ANCO Engineering Inc. 1983) was carried out using shake table tests on a pendulum ceiling that is only supported via vertical hanger wires. The response of this ceiling under the applied ground motion excitation was compared with a similar specimen restrained with 45-degree splay wires. The comparison showed that the pendulum ceiling had lower peak acceleration but higher peak displacement. In another study (Yao 2000) direct-hung suspended ceiling system commonly used in Taiwan was tested on a shake table. The ceiling specimens did not have perimeter connections and were hung via vertical wires as per the recommendations of (CISCA). The period of the hanging ceiling was measured to be close to that of a simple pendulum. Where ceilings were not restrained from movement in transverse direction via small perimeter cross tees, failure was observed due to separation of grids from edges and side sway in main tees. When transverse cross tees were placed between ceiling main tees and edges, more rigid in-plane behaviour was observed and damage was caused by deformation of grid members and their connections. In a preliminary study carried out in the University of Canterbury (Robson et al. 2014), the feasibility of a ceiling that performs like a simple pendulum was investigated. The study consisted of a simple numerical phase followed by experimental tests focusing on the response of a hanging mass to a series of sinusoidal and ground motion excitations. Through this primary investigation it was concluded that: i) The length of the rod has an impact on the natural frequency of the pendulum and therefore affects its response to a particular motion, ii) Varying the hanging mass has a negligible effect on pendulum peak displacement and does not change its natural frequency, iii) Increase in displacement was observed at input resonance frequencies, iv) Increasing the amplitude of input acceleration elevated the peak displacement.

Following these preliminary evaluations, the primary objective of this study is to investigate the feasibility of describing a suspended ceiling's behaviour according to the pendulum theory. This was done through a series of shake table tests to gain an understanding of how various parameters such as mass, excitation amplitude and excitation frequency affect the response of fully floating ceiling specimens. The peak displacement response of the ceiling under seismic excitation is also evaluated as a key factor in determining the architectural and structural feasibility of the design.

2 DESIGN OF THE EXPERIMENT

2.1 *Test specimen*

The ceiling specimen tested is 2.15m×4.55m in size (Figure 2) and is hung from the test frame roof joists through a number of steel wires measuring 450mm in length. These hanger wires are a minimum of 12-gauge galvanized, soft annealed mild steel wire (ASTM C636/C636M-13). The ceiling consisted of DONN brand DX30D-3600 main tees and DX30M-1200 cross tees, both of which are standard grids. The ceiling tiles were 1200mm × 600mm USG Boral Radar ClimaPlus which are one of the common tiles used in the area (USG Boral 2012, DONN® Brand Grid 2011). The fully floating ceiling is 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 tees via 3.2mm aluminium rivets.

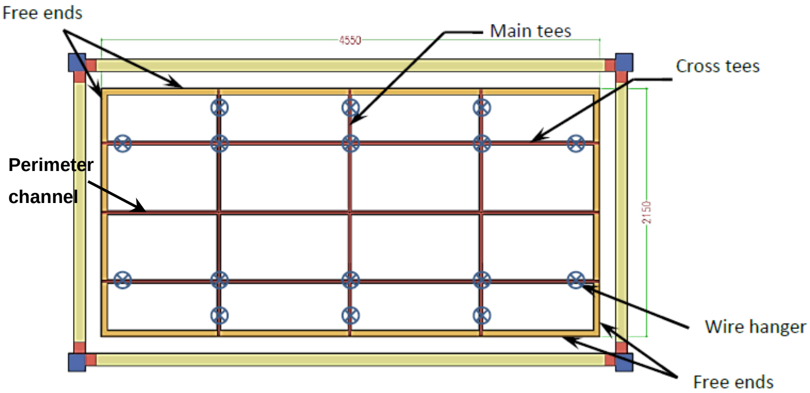

Figure 2 – Plan view of fully-floating ceiling specimen

Three configurations of this specimen were tested with slight variations in hanger layout and ceiling weight (Figure 3). In the first configuration, the ceiling is tested with average tiles weighing approximately 2.75kg each (3.82kg/m^2) making the ceiling 37.4kg in total. In this configuration, hanger wires are placed according to layout A shown in Figure 3a. To find the effect of weight on the response of the ceiling, 22kg of extra mass was spread on the ceiling. In the next setup, the extra mass was removed and hanger wires were changed to fit layout B presented in Figure 3b. The natural period of the ceiling was expected to be 1.37s according to Equation 1.

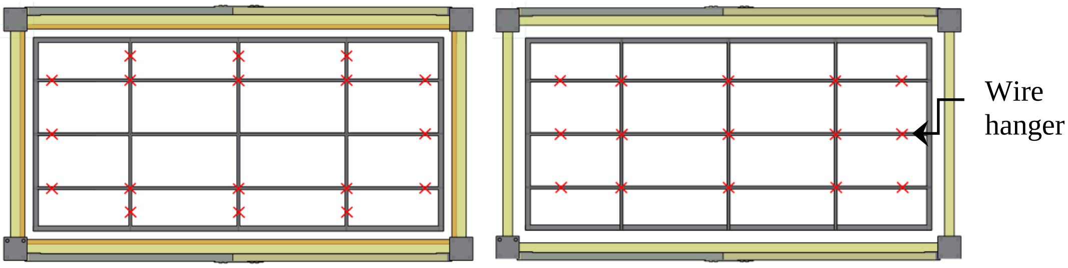

Figure 3 – Ceiling specimen with hanger (a) layout A (left) and (b) layout B (right)

2.2 *Test setup and instrumentation*

The setup was constructed on a 2m by 4m unidirectional earthquake ground motion simulator. The frame erected (Figure 4) is 5.20m long, 2.65m wide and 2.8m high and can accommodate a 2.15m by 4.55m ceiling. The frame is cross-braced in the direction of excitation, E-W. Connections at column bases are pinned and rigid fixed end plate connections are used at beam to column joints. At ceiling hanging level, 450mm from the top, timber beams are fixed to the columns on four sides to provide perimeter support. The frame used in this study is relatively rigid with a horizontal frequency of 12.5Hz.

A total of 12 instruments were used for recording the test outputs in this series of tests including accelerometers and potentiometers. A schematic view of the location of these instruments is shown in Figure 4. 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 (Hedrick Lab) in MATLAB to derive the displacement of the ceiling.

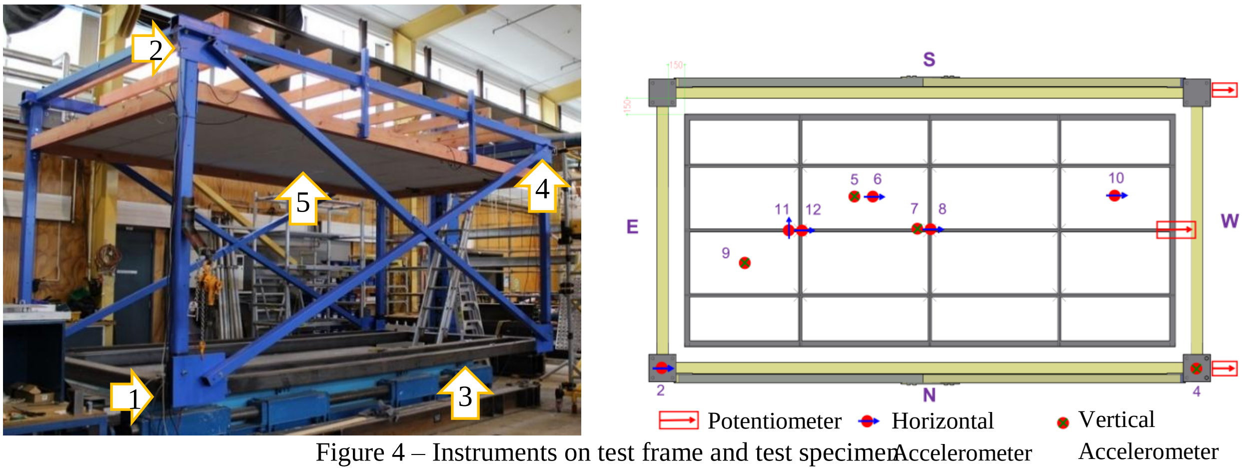

Figure 4 – Instruments on test frame and test specimen

Table 1 – 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*

The first objective of these series of tests is to understand the response of the fully-floating ceiling system to different input motions. For this purpose, it is more desirable to have a controlled loading regime through which the effect of various parameters of excitation can be separately investigated. Therefore, a series of sinusoidal motions varying in displacement amplitude and frequency were chosen as input motion for these tests. This provided a variety of input Peak Floor Acceleration (PFA) s applied on the ceiling. Figure 5 shows the acceleration recorded on the shake table and on the top of the frame over a range of different frequencies. Following these tests using sine waves, a suit of ground motions were used as the input motion. Ground motions were chosen such that a variety of frequency content could be applied to the specimens.

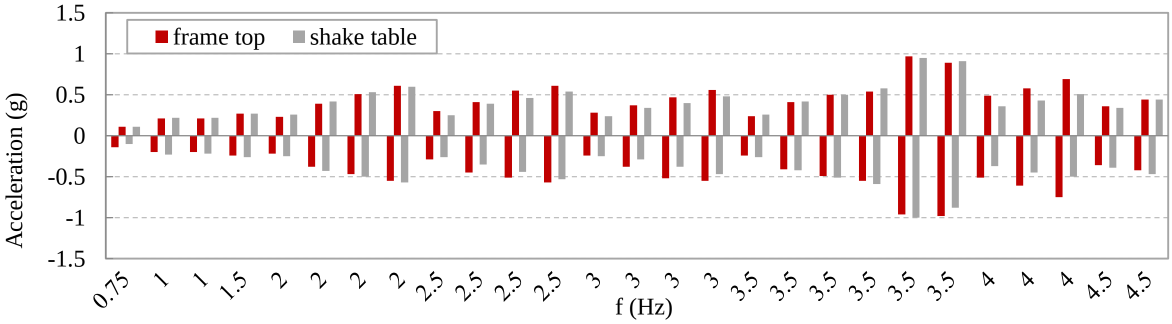

Figure 5 – Acceleration recorded on shake table and acceleration response on frame top

3 RESULTS AND DISCUSSIONS

3.1 *Natural properties of the specimen*

Values of natural frequency and damping ratio of the ceiling specimen at different configurations were measured using the free vibration phase of experiments and/or transfer function (Table **2**).

Table 2 – Natural frequencies and damping ratios obtained from ceiling

Test description	Average natural frequency [Hz]	Average damping ratio
Fully-floating ceiling – Hanger layout A	0.774	0.012
Fully-floating ceiling with additional mass	0.751	0.0074
Fully-floating ceiling – Hanger layout B	0.772	0.0111

The comparison of the values of natural frequency calculated at each test showed that the frequency of the ceiling remains the same regardless of the frequency content of input motion and is similar to the one derived by Equation 1. Also, increasing the weight of the ceiling or changing the wire hangers' layout did not affect the natural frequency of the system significantly. However, a 38% decrease was recorded in the damping ratio as the total weight of the ceiling was increased by 59% (22kg). This reduction is expected based on the interrelation between damping ratio and mass, $\xi = \dfrac{c}{2m\omega_n}$.

3.2 *Frequency content of input motion: Sine motion and Ground motion*

In order to confirm the direct relation between the frequency of the input motion and the displacement, sine wave motions with a range of displacement and acceleration amplitudes were applied to the specimen. The frequencies of the input sine waves varied between 0.75Hz, which is quite close to that of the ceiling, and 4.5Hz. Figure 6 below shows the values of peak displacement recorded at different input frequencies for three ceiling specimens (i.e. Ceiling with wire hanger layout A (WPA) & B (WPB) and ceiling with additional mass). As the frequency of the sine wave approaches the natural frequency of the specimen i.e. 0.78Hz a significant increase in displacement can be observed.

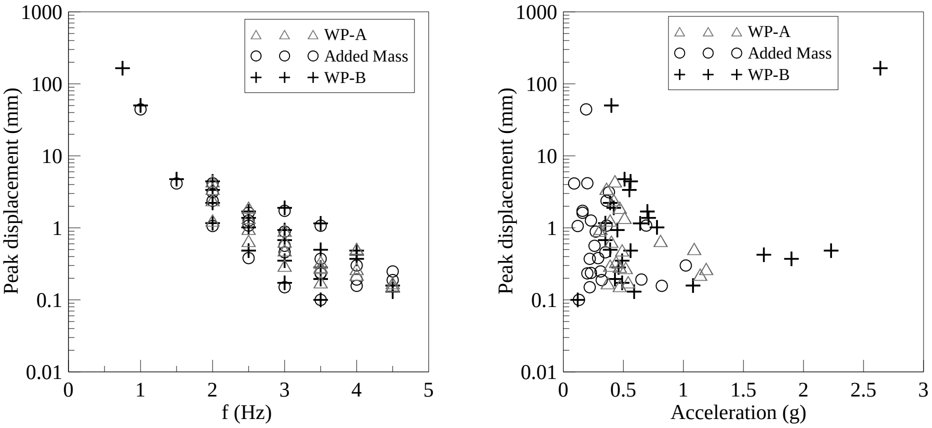

Figure 6 – Displacement of the specimen at various sinusoidal input motions

Values of peak acceleration induced in the ceiling specimen were recorded through accelerometers in various locations of the test setup (See Figure 4). Figure 5-right shows acceleration vs. peak displacement recorded at the centre of the ceiling grid during sinusoidal tests. The results show that the amount of displacement is not significantly dependent on the amplitude of input acceleration. A wide range of displacements were recorded at similar response accelerations.

In the first series of tests on the fully-floating ceiling with hanger layout A, two sets of ground motions were used: i) filtered and ii) unfiltered. The bandwidth filtering was performed such that the input acceleration time history would exclude the frequency content in the vicinity of the natural frequency of the ceiling specimen. Graphs in Figure 7 below show the frequency content derived for these acceleration time histories with and without filtering. Based on these observations it can be concluded that the effective element did not appear to be the amplitude of acceleration but rather the frequency contents of the motion.

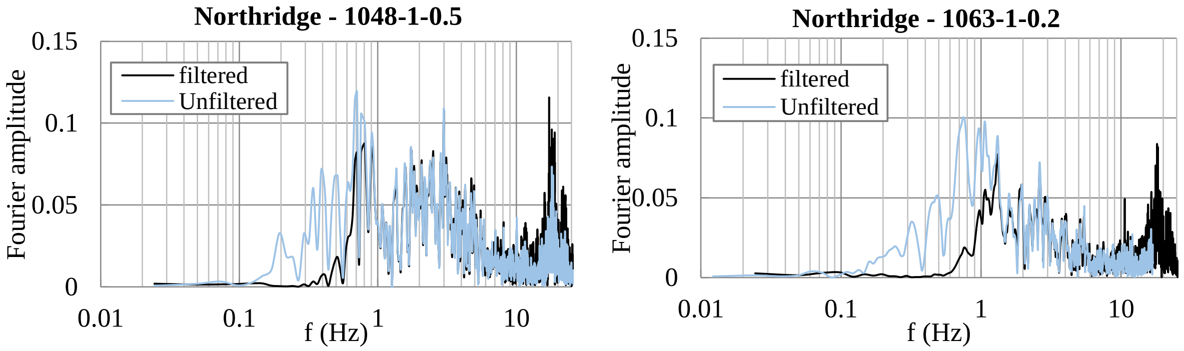

Figure 7 – Fourier amplitudes of ground motions with and without filtering

As it can be observed in Table 3, the frequency content of the input motion has a clear effect on the displacement recorded. In case of the unfiltered Northridge-1063-1 record for instance, although the input acceleration recorded at frame top is smaller than the filtered record, a significantly larger displacement was recorded in the ceiling specimen due to resonance. The large acceleration recorded at ceiling centre in this test, i.e. 6.52g, was the result of ceiling displacement exceeding the provided perimeter gap and pounding between ceiling and perimeter timber beams. Similar trends were observed in other ground motion records applied.

Table 3 – Peak displacement and accelerations at ground motions with and without filtering

Ground motion	Acceleration frame top (g)	Acceleration ceiling centre (g)	Peak displacement (mm)
1063-1-0.2	0.36	0.56	30.92
U*-1063-1-0.2	0.29	6.52	173.67
1048-1-0.5	0.30	0.62	119.86
U*-1048-1-0.5	0.24	0.50	169.76

** Note: U stands for unfiltered*

3.3 *Propagation of input acceleration*

In an earlier phase of this study, performance of perimeter-fixed ceilings was evaluated through shake table experiments (Pourali et al. 2015). The perimeter-fixed ceiling specimens were tested on the same frame as in this paper and were of approximately similar structural properties e.g. grid types, tile weight and size. They only varied in their form of connection to the supporting test frame: attached to the perimeter on two intersecting sides and free on two opposite sides. Figure 8 below shows the amplification of accelerations recorded on ceiling grid and tile relative to acceleration on top of the frame for the perimeter-fixed ceiling.

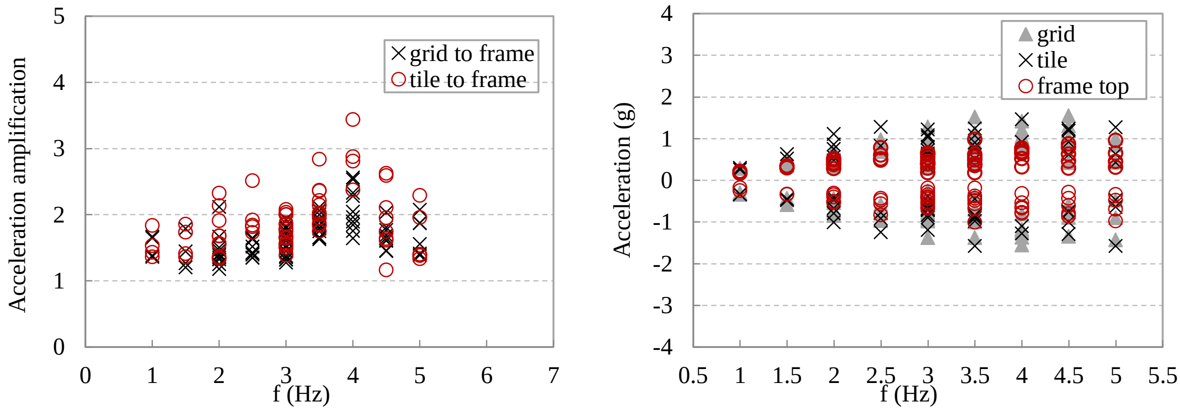

Figure 8 – Acceleration amplification and acceleration values in perimeter-fixed ceiling specimen – Sinusoidal motion (Pourali et al. 2015)

For comparison, values of acceleration recorded on the same locations on three different variations of the fully-floating ceiling specimen are shown in Figure 9. As it can be seen, in fully-floating specimens, contrary to the perimeter fixed type, values of acceleration recorded on the tile and grid are generally close to the input acceleration on frame top except for the results form 4Hz tests which are affected by resonance in test frame. The amplification factors are mainly below 2 with a large number of results being less than one. This indicates that in many cases, the acceleration recorded on the ceiling was less than the input acceleration. This is different from the results obtained from perimeter-fixed specimen in Figure 8 where for all tests, the amplification factor is between 1 and 3.5.

In the second row of graphs in Figure 9 the effect of resonance on the specimen can be observed where ceiling was excited at 0.75Hz frequency which is close to the natural frequency of the specimen i.e. 0.78Hz. At this frequency, large displacements were observed and high accelerations were recorded on the ceiling due to pounding against perimeter beams.

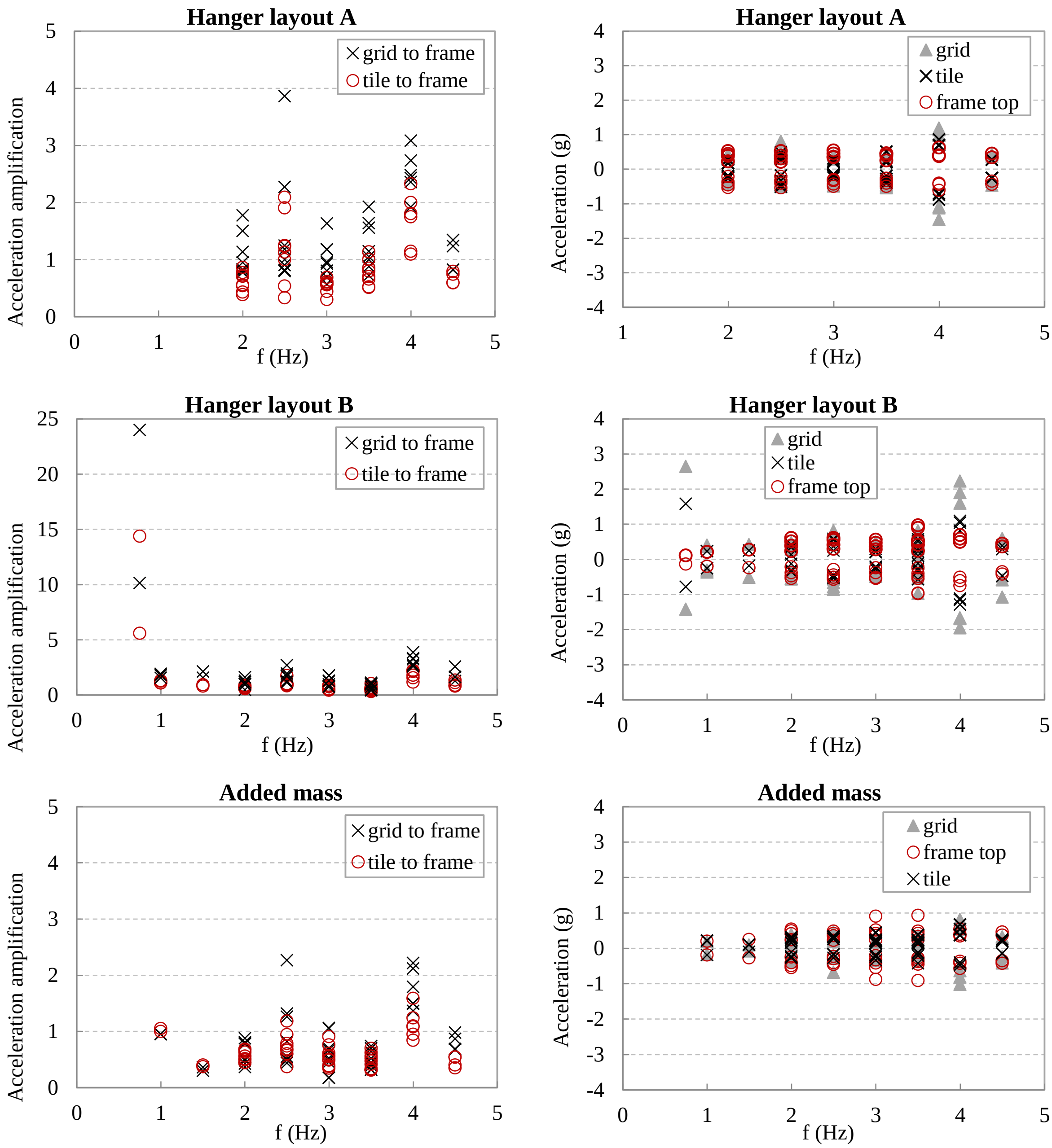

Figure 9 – Horizontal acceleration amplification in different fully-floating ceilings – Sinusoidal motion

3.4 *Ceiling weight*

As discussed in Section 3.1, increasing the mass of the ceiling by 22kg did not have a significant effect on the natural frequency of the system and only a slight decrease was observed. However, the damping ratio reduced as mass was added. The pattern of the displacement did not show a noticeable change. Comparing values of peak displacement in ground motion tests show either similar or slightly increased values for the heavier specimen (Figure 10). These differences vary between 1-6 millimetres. Since all displacement data in this series of tests are derived from digitised videos, differences in values of peak acceleration in sinusoidal tests should be evaluated with considerations for the errors in measurement and digitising.

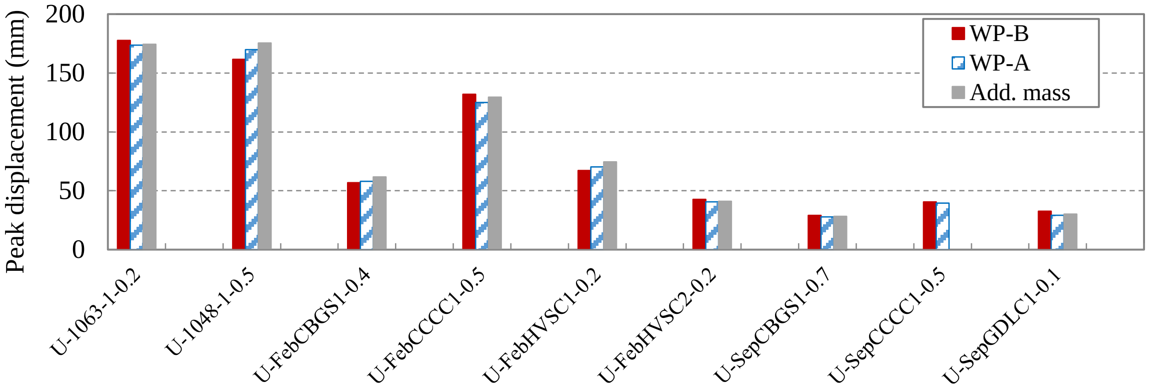

Figure 10 – Peak displacement in ground motion tests

Similar comparison has been made for displacements recorded in sinusoidal tests (Figure 11). As can be observed, the differences are fairly small and rather negligible considering the errors in digitising and measurement.

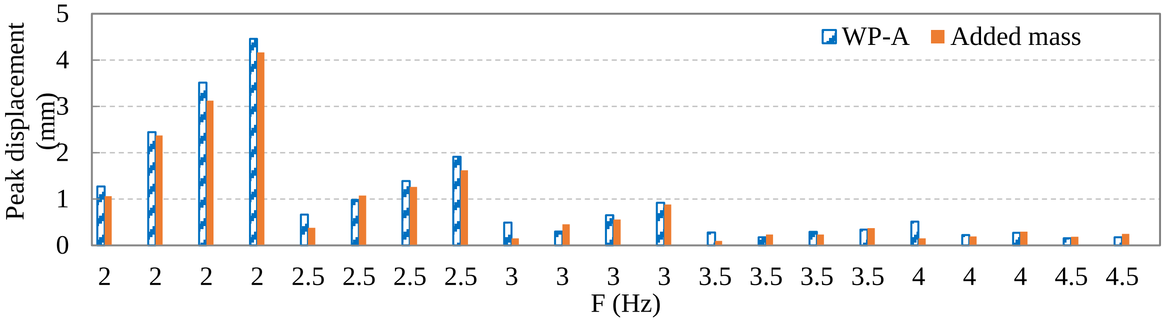

Figure 11 – Comparison of peak displacement in sinusoidal tests, hanger layout “A” with and w/o added mass

In addition to displacement, the values of peak horizontal acceleration recorded at the centre of the ceiling grid are also compared in Figure 12. Due to limited time and difficulties of installation, instead of using heavy tiles, small sand bags were distributed over ceiling grids joints in a symmetrical pattern. In general, ceiling tiles are loosely fitting in grid modules with a minimum gap of 5mm and were observed to vibrate in vertical and horizontal directions. The placement of these masses limited the vibration and sliding in ceiling tiles. Figure 13 below shows two sets of acceleration time histories for two sinusoidal tests of similar table input motion -2.5Hz, 4mm- with and without added masses. The accelerometers are on two grid joints. In comparison to the other tiles, the tiles placed on the central joint were more restrained by sand bags, as a result of which smaller accelerations were measured at this area. The recorded response acceleration time history also had a more even distribution with rare spikes in the response. Comparing horizontal and vertical acceleration time histories in the ceiling shows that these spikes mainly result from the vertical excitation of the ceiling tiles. For the heavier ceiling, majority of the recorded response accelerations were smaller than those of the lighter one. Similar behaviour was observed in other sinusoidal and ground motion tests.

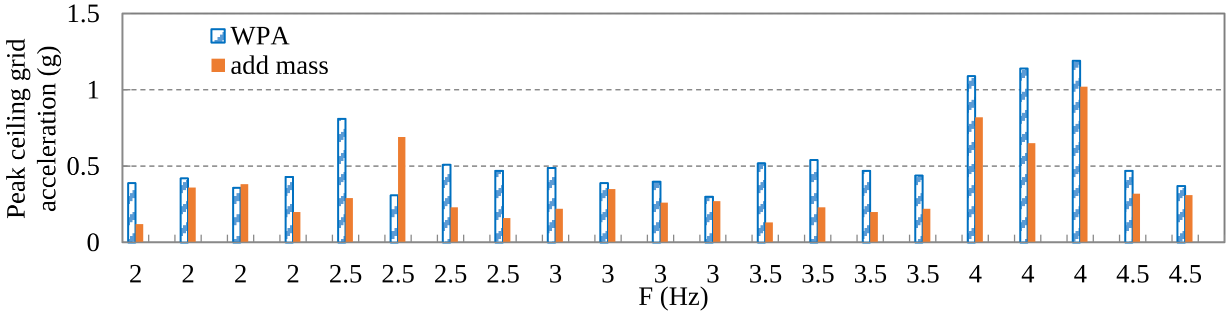

Figure 12 – Comparison of peak acceleration measured on ceiling centre, hanger layout A, with and w/o added mass

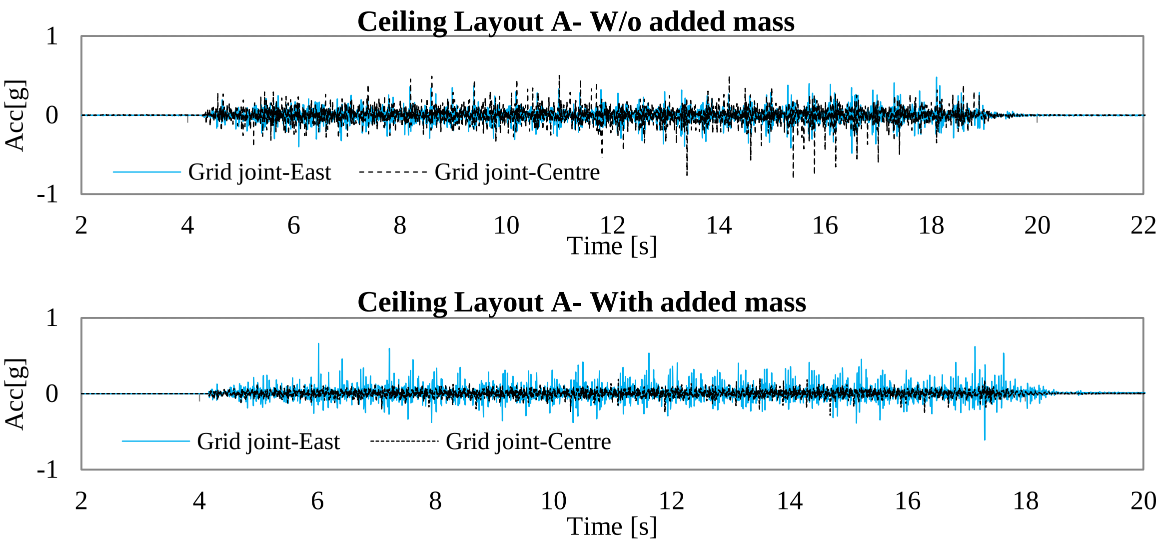

Figure 13 – Acceleration time histories on ceiling grid in sinusoidal tests, hanger layout "A" with & w/o added mass

3.5 *Arrangement of wire hangers*

As discussed earlier in Section 2.1, two layouts were used for the hanger wires connecting the ceiling specimen to the roof of the test frame. As shown in Table 2 in Section 3.1, changing the layout of the wire hangers does not affect the natural period and damping ratio of the specimen. This is expected as the period of a simple pendulum is a factor of pendulum length and gravity acceleration.

The first observation made after the change of wire layout was the swinging pattern of the ceiling. As the hangers got more concentrated in the centre of the ceiling, the displacement in the direction perpendicular to the direction of excitation increased significantly and ceiling specimen followed a more circular displacement pattern rather than linear. These patterns are shown in **Error! Reference source not found.**Figure 14. Based on these results and observations, it is concluded that a symmetrical and evenly spread-out hanger wire layout is more advantageous in the fully-floating ceiling tested. In order to eliminate the haphazard movement of the ceiling, hangers are required at most 200mm from the terminal ends of all grid members.

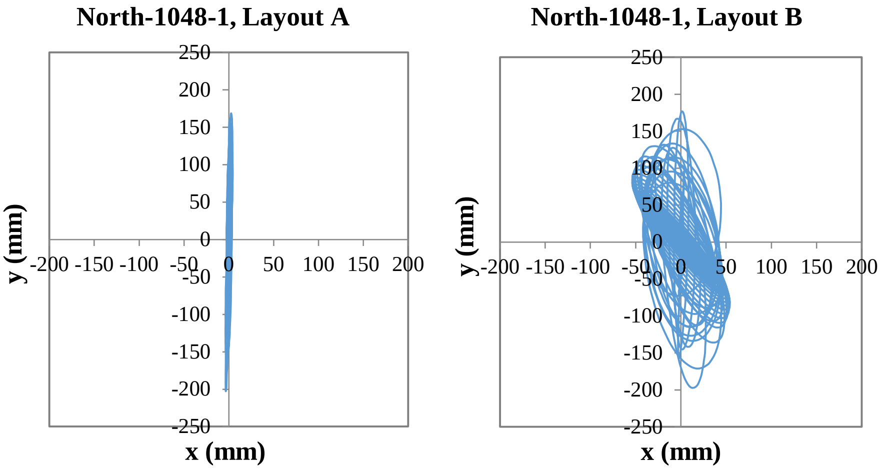

Figure 14 – Position of a tracked point on the ceiling with hanger layouts A and B

Comparisons made between the values of displacement in ceilings with two different hanger layouts show that despite the change in the pattern of oscillation, the peak displacements were not notably different (Figure 15).

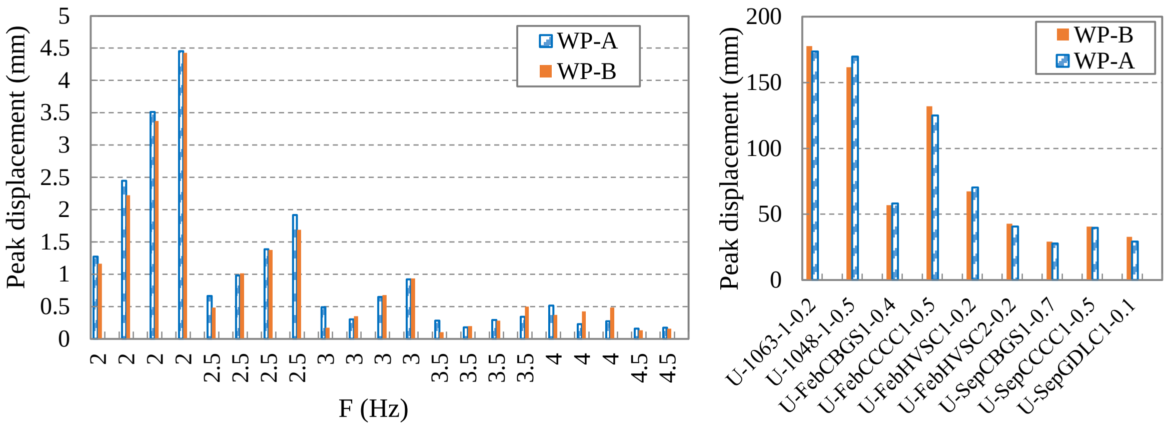

Figure 15 – Displacement with hanger layouts A and B

4 CONCLUSIONS

A pendulum-type fully-floating ceiling has been tested on shake table using sinusoidal and earthquake input motions.

- The natural frequency of the fully-floating ceiling tested was independent of the ceiling total mass. This is consistent with the simple pendulum theory.
- Changing the number and arrangement of the vertical wire hangers did not affect the frequency of the fully-floating ceiling. However, a more spread-out layout of hangers covering perimeters rather than centre of the ceiling reduced the displacement perpendicular to the direction of excitation. Since this change of layout did not affect the peak displacement in specimens it was not further discussed herein.
- The accelerations induced in ceiling grids were mostly smaller than the input acceleration at ceiling support level, as long as pounding between ceiling and frame did not occur.
- Larger displacements were recorded at frame input frequencies close to the natural frequency of the ceiling. Large input accelerations did not independently result in large displacements.
- Adding mass on the ceiling grid and tiles limited the vibrations and sliding in ceiling tiles, resulting in fewer acceleration spikes and smaller peak acceleration recorded on ceiling grids.

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