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INFLUENCE OF PERIMETER SUPPORTS ON THE SEISMIC RESPONSE OF PLASTERBOARD SUSPENDED CEILING SYSTEMS

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Abstract

Many modern buildings across the world are equipped with suspended ceiling systems for functional and/or aesthetic requirements. Suspended ceiling are broadly classified as 1) Lay-in-tile suspended ceiling systems (LSCS); 2) Plasterboard suspended ceiling systems (PSCS). These systems are generally supported from the floor through suspenders. It may also be supported at the perimeter by the surrounding wall(s). This paper presents a study on a test set-up comprising a test frame representing a single-story building and a PSCS specimen subjected to a series of ground motions in its principal horizontal directions. The PSCS specimen was suspended through ceiling angles (suspenders) from the roof of the test frame. Properties of ceiling angles were different in the two principal horizontal directions. Ambient damping of the test frame and PSCS system were determined through hammer tests. Damping ratio was 1.5% and 1.3% for the test frame, and 6% and 8% for the PSCS specimen in two orthogonal horizontal directions. Natural period of the PSCS specimen increased with increase in shaking level: from 0.3 s to 1.0 s in one direction, and from 0.9 s to 1.0 s in other. The two directions are referred to as "long" and "short", respectively. The change in natural period was associated with the nonlinear response of ceiling angles at their respective lower ends. Legs of the ceiling angle deformed in and out of their respective planes during the experiments. Moment-rotation behavior of the connection between ceiling angle and roof of the test frame was determined through static tests. An analytical model was developed for the analysis of the PSCS systems. The model included the behavior of connection between the ceiling angle and roof. It was assumed that the legs of the ceiling angle deform only in their plane. Natural period of the PSCS specimen obtained through the analytical model compared well with the experimental observations before first level of shaking in long direction. The natural period obtained from the analytical model in the other horizontal direction was very different from experimental values, which could be attributed to difference in the fabrication of connection between the roof of the test frame and ceiling angle during dynamic and static tests. The model was able to capture peak accelerations in the plasterboard reasonably well in the long direction. The model, however, was not able to capture the change in natural period with increase in shaking intensity, which could be due to the assumption on in-plane deformation of the legs of the ceiling angles. The model was extended to incorporate the effect of different supports at the perimeter. Support conditions included contact between the horizontal metal frame and the test frame with coefficients of friction set equal to 0.1 and 0.7, and links between test frame and horizontal metal frame. Relative displacement between the test frame and PSCS specimen decreased substantially with the introduction of a perimeter support. Peak acceleration and response spectra corresponding to the plasterboard also were considerably altered by the choice of a perimeter support in the model.

Keywords: Plasterboard; Suspended ceiling; Perimeter supports, Link; Friction; Free

1. Introduction

Suspended ceiling systems are generally used in building structures for functional and aesthetic reasons. Two broad classes of suspended ceiling systems are common: lay-in-tile suspended ceiling system (LSCS) and plasterboard suspended ceiling system (PSCS). These systems are supported by the structural members in a building and may be connected to other non-structural components, for example, fire sprinklers. In the event of an earthquake, ceiling systems are often damaged at shaking intensities much lower compared to that corresponding to damages in structural systems. Failure in the ceiling systems can cause life-threatening injuries to the inhabitants, obstruct the post-earthquake evacuation, and affect the functionality of a building, besides causing financial losses (e.g., [1], [2]).

This paper focuses on PSCS, which generally comprises of a plasterboard, a horizontal frame supporting the plasterboard, and suspenders supporting the horizontal frame. The horizontal frame at its ends can be connected to the walls at its perimeter or may be simply rested. Response of these systems can be complex due to semi-rigid connections and thin members, and the multiplicity of possible support systems and support conditions. Consequently, the methods for analysis and design of these systems are not well established. The configuration and installation procedure for PSCS are usually determined based on prescriptive approaches (e.g., [2], [3], [4]) or seismic qualifications testing (e.g., [5], [6]).

This paper presents the results of a series of experiments on a PSCS specimen suspended using struts with the horizontal frame unsupported at the perimeter. A simplistic analytical model is developed to simulate the experimentally observed responses. The model is extended to include additional support conditions at the perimeter: “simple” and “linked.” The simple support condition refers to the members of horizontal metal frame resting on the test frame supporting the PSCS specimen. Two values of coefficient of friction between the horizontal metal frame members and test frame, namely, 0.1 and 0.7. “Linked” support condition refers to the members of horizontal metal frame members connected to the test frame through pin connections. The analytical study provides insights into the influence of support conditions on the response of the PSCS specimen.

2. Dynamic tests

Dynamic tests were carried out in the structural engineering laboratory at Indian Institute of Technology Kanpur. Details of these tests are presented in the sections below.

2.1 Test set-up

The test set-up comprised of a uniaxial shaking table, a test frame, and the PSCS specimen suspended from the top of test frame. The test set-up is shown in Fig. 1. The base dimension of shaking table is 1,500 mm × 1,500 mm. The shaking table can take a maximum payload of 40 kN. A maximum possible displacement, velocity and acceleration of 75 mm, 1.5 m/s and 3g, respectively, can be achieved by the shaking table. Additional details on the shaking table are presented in Sinha and Rai [7].

The test frame represents a single-story building. Its base dimension is 1,500 mm × 1,500 mm, and the total height is 3,000 mm. The dimensions of its roof are 3,000 mm × 2,440 mm. The frame is made of steel sections. Further details on the test frame are presented in Matale [8].

Fig. 2 presents a schematic of the PSCS specimen. The specimen is suspended from the top of test frame through four suspenders (or ceiling angles), which are made of corrugated steel. Ceiling angles are L-shaped with the length of the two legs of an angle being 25 mm and 10 mm. Thickness of the two legs of the angle is 0.5 mm. The four ceiling angles are attached to a horizontal metal frame that supports the plasterboard. The frame is “free” from the perimeter. This support condition is referred to as “free” support condition. This frame remained elastic during the experiments. Further details on the horizontal metal frame are presented in Matale [8].

Fig. 1 – Test set-up

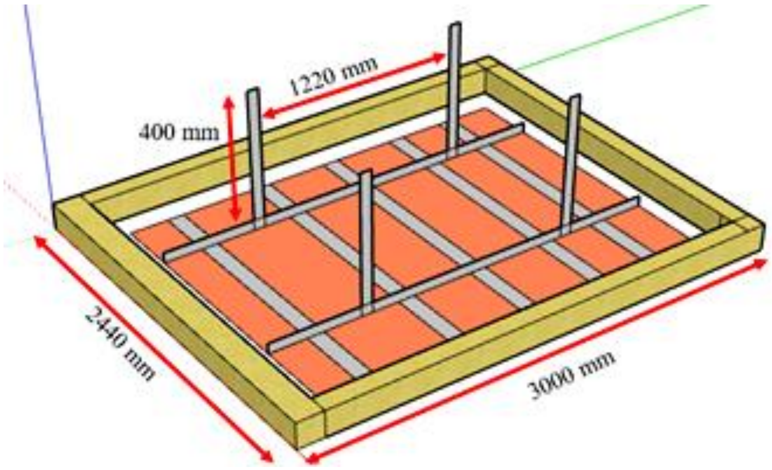


Fig. 2 – A schematic of PSCS specimen

Three accelerometers were placed at center of the top of the test frame: one in each of the two principal horizontal directions and one in the vertical direction. Five accelerometers were placed on the plasterboard: four at each side of the plasterboard to measure the horizontal acceleration along the edge, and one at the center of the plasterboard in the vertical direction. Two LVDTs were placed between the plasterboard and the test frame to measure the relative horizontal displacements in the two principal horizontal directions. Strain gauges were placed at top and bottom of each leg of the suspenders (ceiling angles). Additional details on the instrumentation are presented in Matale [8].

2.2 Testing protocol

Hammer tests were conducted to evaluate the dynamic characteristics of the test frame without the PSCS specimen attached. The PSCS specimen was attached subsequently to the test frame and the hammer tests were carried out again. The test set-up was then subjected to 11 levels of ground shaking in the long direction and five levels of ground shaking in the short direction. The long and short directions correspond to the longer and shorter edge of the test frame, respectively. Peak ground accelerations (PGAs) of the ground motions ranged between 0.05g and 0.70g (0.05g and 0.25g) for the long (short) direction. Ground motions were realized by amplitude scaling the recorded Taft motion. Spectral shape of Taft motion compares well with the design spectral shape considered by Indian earthquake code IS 1893 [9]. Fig. 3 presents the response spectrum of the Taft motion with peak ground acceleration of 0.36g. Also shown in the figure is the maximum considered spectrum for seismic zone V of IS 1893 [9].

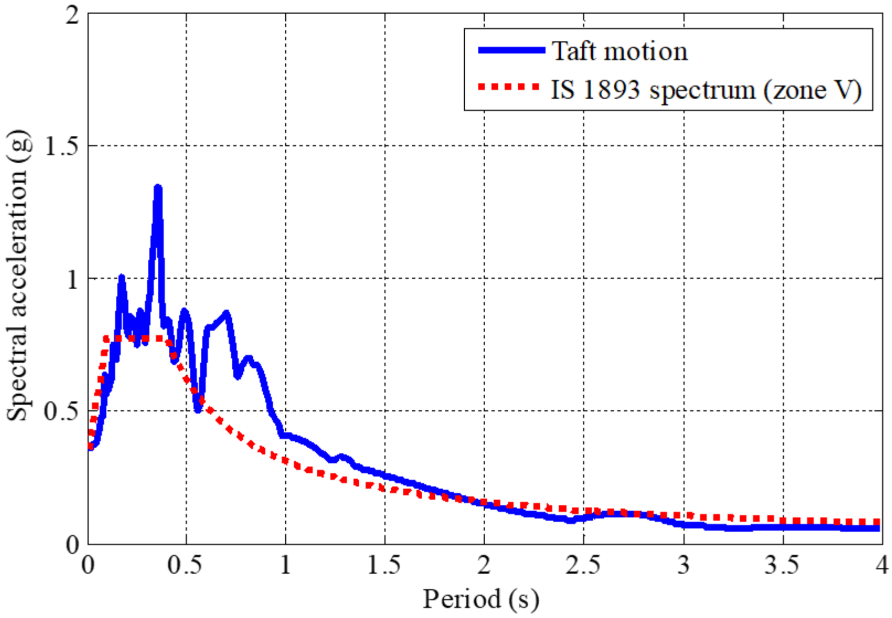


Fig. 3 – Response spectrum for Taft motion and IS 1893 design response spectrum

The test set-up was first oriented with the short edges of the test frame, short edges of the plasterboard and short leg of the ceiling angles oriented along the direction of shaking. A white noise test was conducted first. The system was then subjected to Taft motion with PGA of 0.05g (Level 1). A white noise test was conducted again. The test frame (along with the PSCS specimen) was rotated by 90 degrees so that the long edges of the test frame and plasterboard (and long leg of ceiling angle) were along the direction of shaking. The aforementioned tests were repeated. The tests were performed in both directions at multiple levels of shaking. The system was subjected to the Taft motion scaled to following PGAs in long direction: 0.05g, 0.10g, 0.15g, 0.20g, 0.25g, 0.30g, 0.35g, 0.40g, 0.50g, 0.60g, and 0.70g (levels 1 through 11). The system was subjected to only first five levels of shaking in the short direction (the plasterboard had impacted the test frame during the fifth level of shaking in short direction).

2.3 Results

The fundamental period of the test frame without the PSCS specimen was 0.050 s, 0.044 s and 0.064 s in the short, long and vertical directions, respectively. The natural period in the vertical direction was associated with the out-of-plane vibration of the roof of the test frame. The fundamental periods of the frame (with PSCS specimen attached) were 0.073 s, 0.068 s and 0.090 s in the three directions, respectively. The natural periods associated with the vibration of the PSCS specimen was 0.91 s, 0.34 s and 0.09 s in the three directions, respectively.

Acceleration records corresponding to the white noise tests were filtered so that the remaining signal had the frequencies close to corresponding fundamental frequencies. Damping of the system was determined using the logarithmic decay approach (e.g., [10]). Damping ratios of test frame along short and long directions were 1.3% and 1.5%, respectively. Damping ratios associated with the vibration of PSCS specimen were 8% and 6% in the two directions, respectively.

Fig. 4 presents the fundamental period of the PSCS specimen before and after each level of shaking. The fundamental period increased from 0.91 s (0.32 s) before Level 1 shaking to 0.99 s (0.69 s) after Level 5 shaking in short (long) direction. As noted previously, tests were performed only in the long direction afterwards, and the fundamental period of the PSCS specimen in long direction increased to 0.99 s at the end of Level 11 shaking.

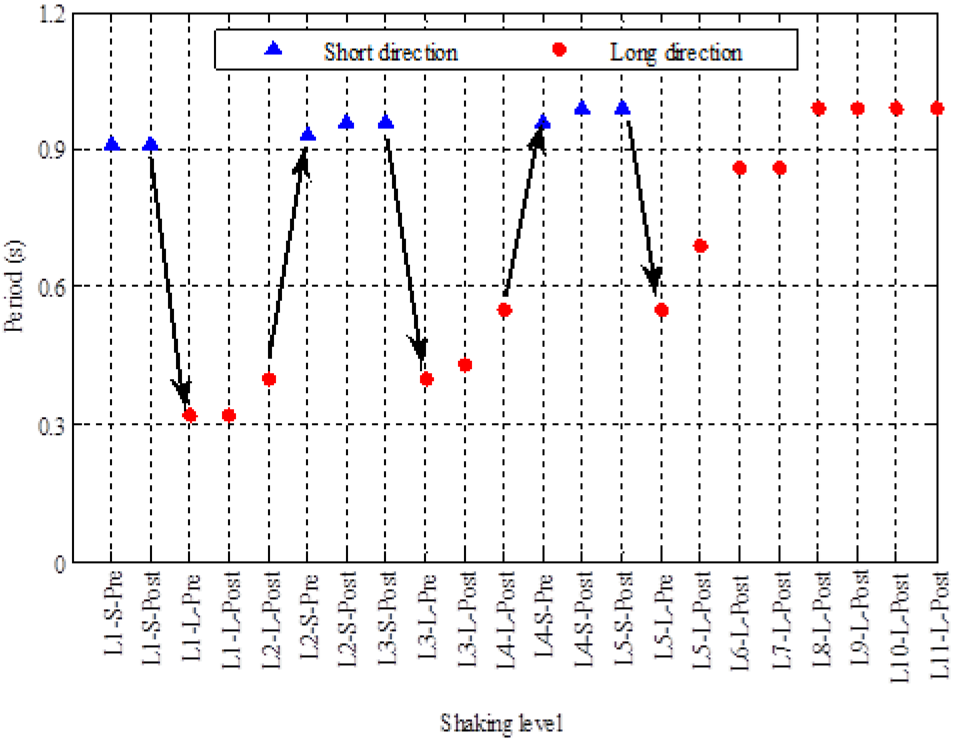
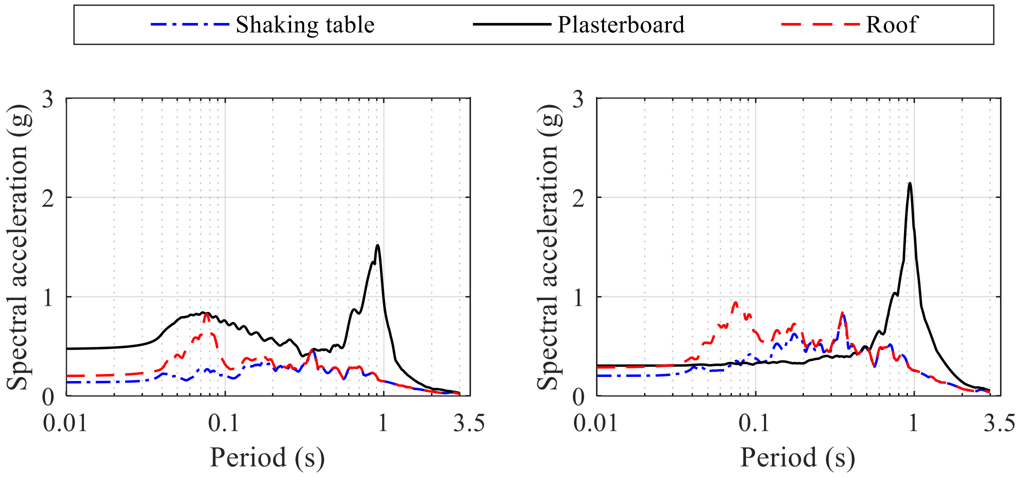


Fig. 4 – Natural period of the PSCS specimen

Figs. 5(a) and 5(b) present the response spectra at different locations in the test set-up for shaking levels 2 and 4 in the short direction, respectively. Peak accelerations recorded at shaking table, roof of the test frame and plasterboard were 0.13g, 0.20g and 0.47g, respectively, for Level 2 shaking. These values were 0.20g, 0.29g and 0.30g, respectively, for Level 4 shaking. A peak in the spectrum corresponding to the roof is observed at 0.075 s, which is close to the fundamental period of the test frame in short direction. Similarly, a peak in the spectrum corresponding to the plasterboard is observed at 0.91 and 0.94 s for shaking levels 2 and 4, respectively. These values are close to fundamental period of the PSCS specimen in the short direction.

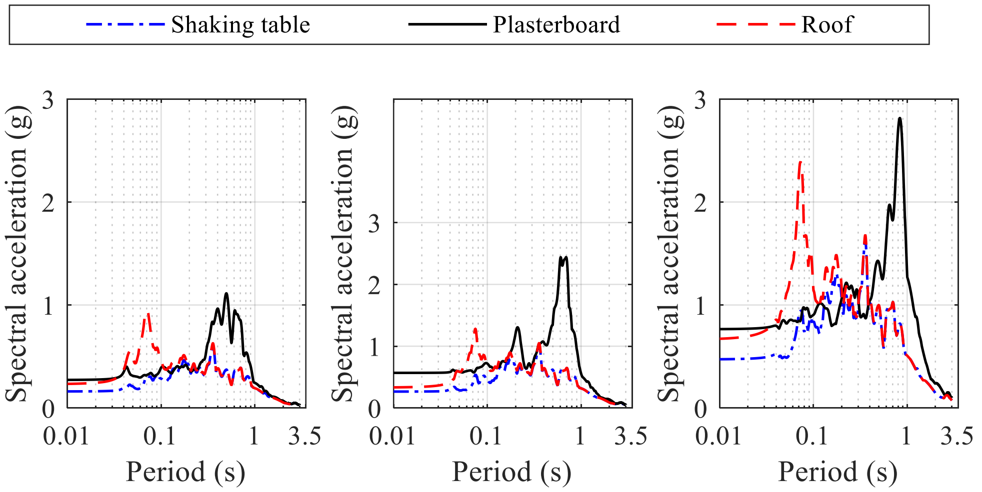
Figs. 6(a), 6(b) and 6(c) present floor spectra for shaking levels 3, 5 and 8, respectively. Recorded peak accelerations at shaking table, (roof of the test frame, plasterboard) were 0.16g (0.23g, 0.27g), 0.26g (0.33g, 0.57g) and 0.47g (0.67g, 0.76g), respectively, for the three levels of shaking. A peak in the spectrum corresponding to the roof is observed at approximately 0.073 s for all three levels, which is the fundamental period associated with the test frame in the long direction. A peak in the spectrum corresponding to the plasterboard is observed at 0.50 s, 0.61 s and 0.84 s at the three levels of shaking, respectively (see Fig. 6). The natural periods at the end of the three levels of shaking were 0.43 s, 0.69 s and 0.99 s, respectively (see Fig. 4).

The test frame and the horizontal metal frame supporting the plasterboard remained elastic during the experiments. The damage was concentrated in the lower ends of the ceiling angles (suspenders). Figs. 7(a), 7(b) and 7(c) present the damage state of a ceiling angle at the end of shaking levels 6, 10 and 11, respectively.



(a) Level 2 (PGA = 0.10g) (b) Level 4 (PGA = 0.20g)

Fig. 5 – Response spectra of acceleration responses at select locations in short direction when the test set up is subjected to earthquake loading in short direction

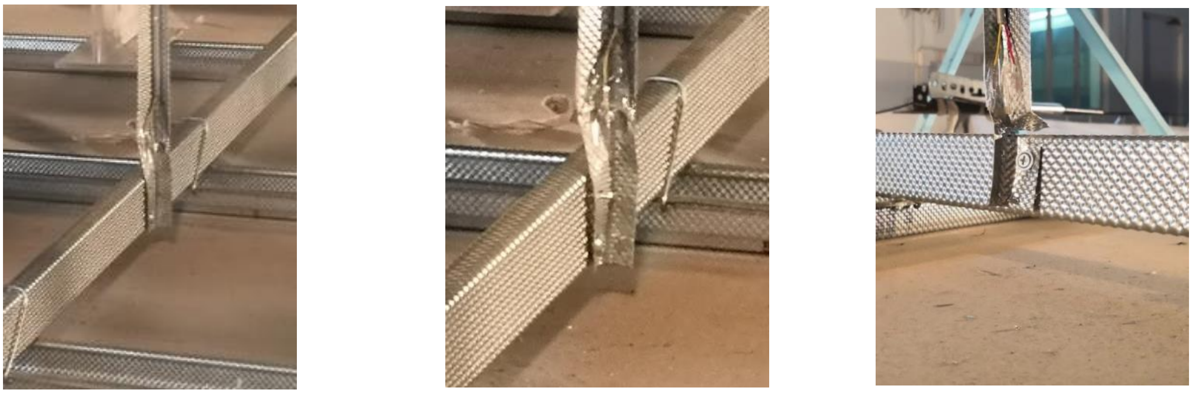


(a) Level 3 (PGA=0.15g) (b) Level 5 (PGA=0.25g) (c) Level 8 (PGA=0.40g)

Fig. 6 – Response spectra of acceleration responses at select locations in long direction when the test set up is subjected to earthquake loading in long direction

3. Static tests: connection between ceiling angle and test frame

As noted previously, ceiling angle was supported by the roof of the test frame. Figs. 8(a) and 8(b) present the test set-up to characterize the moment-rotation relationship for the joint along the short and long legs of the ceiling angle, respectively. These tests were carried out using a Universal Testing Machine (UTM) at Indian Institute of Technology Gandhinagar. Moments at an instant were calculated as the product of force and the length of the connection, and corresponding rotation was calculated as the ratio of vertical displacement and the length of the connection. Three sets of tests for connections in each of the two directions were carried out. Further details on these tests are presented in Matale [8]. Figs. 9(a) and 9(b) present the moment-rotations relationships in the long and short directions, respectively. Average value of initial stiffness in the connection was 84.29 N-m/rad and 95.54 N-m/rad along the short and long legs of the ceiling angles, respectively.



(a) Level 6 (b) Level 10 (c) Level 11

Fig. 7 – Damage in ceiling angle

(a) Test along long leg of ceiling angle (b) Test along short leg of ceiling angle

Fig. 8 – Static tests on connection between ceiling angle and test frame

4. Analytical modeling

Open source software program OpenSees PEER [11] was used to develop the analytical model for simulating the response of the test set-up. Members of the test frame and horizontal frame (supporting the plasterboard) were modeled using *forceBeamColumn* element. A *zeroLength* element was used to model a concentrated spring to simulate the behavior of connection between ceiling angle (suspender) and roof in each principal horizontal direction. Wooden ledges and angles section supporting wooden ledges were collectively considered as a pipe section with cross-sectional dimensions same as members representing walls and roof of the test frame. These members were also modeled using a *forceBeamColumn* element. Plasterboard was modeled using *ShellMITC4* element. A Rayleigh damping of 1.4% and 7% was assigned to the test frame and the PSCS specimen, respectively, in each principal horizontal direction (see Section 2.3).

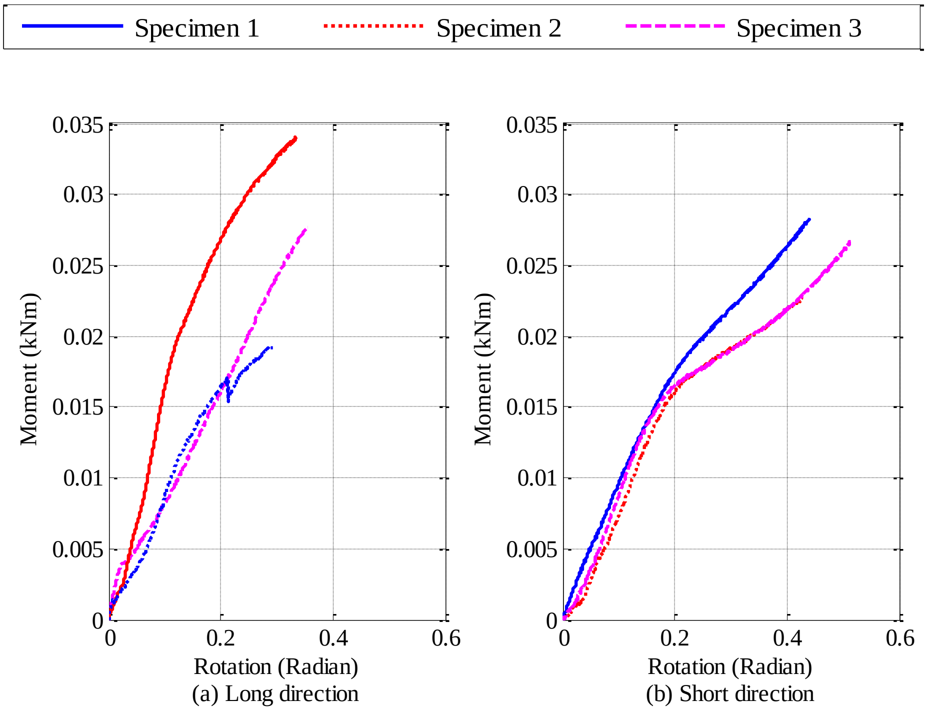
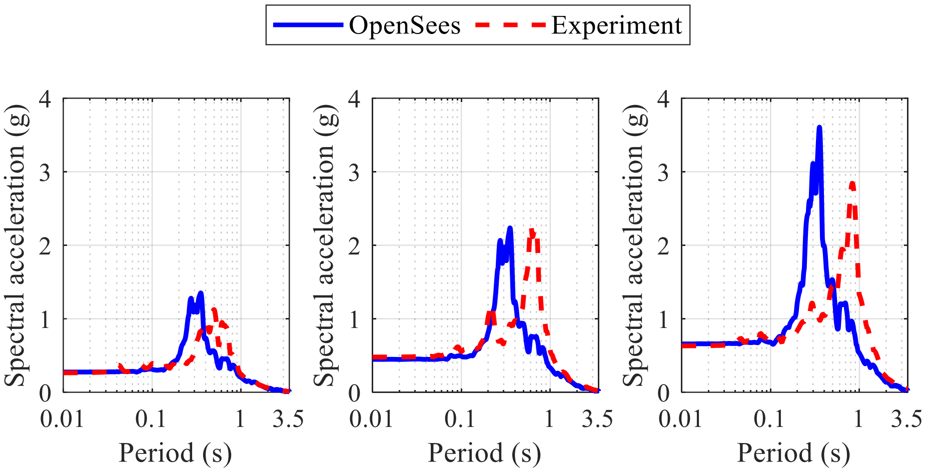


Fig. 9 – Moment-rotation relationships for connections between ceiling angle and test frame

5. Comparison of experimental and analytical results

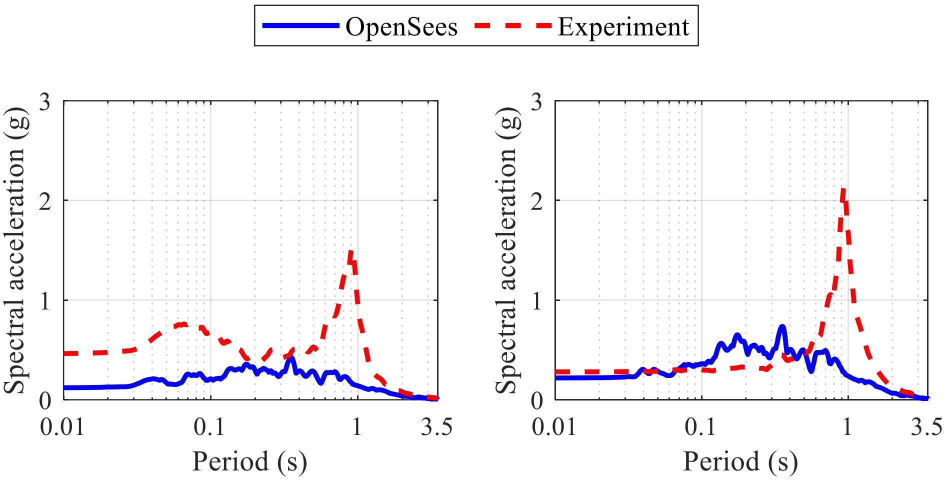
The fundamental period obtained from analytical model of test frame with PSCS specimen along short, long and vertical directions were 0.060 s, 0.056 s and 0.085 s, respectively. These periods compare well with experimental observations. Fig. 10(a) presents the experimentally obtained floor spectrum corresponding to the shaking along the long edge of the test frame for Level 3 shaking. Also presented in the figure is the spectrum obtained through analysis. Panels (b) and (c) of Fig. 10 present results for levels 5 and 8, respectively. Peak floor accelerations obtained through analysis compare well with the experimental results for all levels of shaking. Natural period at which peak spectral acceleration is observed experimentally increases with an increase in level of shaking, which is consistent with observations made for Fig. 4. The same is not observed from the results obtained through analyses. The observed damage in ceiling angles is associated with the out-of-plane deformations in the legs of the angle (see Fig. 7), which is not captured through the analytical model.

Figs. 11(a) and 11(b) presents the experimentally observed and analytically obtained response spectrum corresponding to the acceleration history recorded at the plasterboard along the short edge of the test frame for shaking of levels 2 and 4, respectively. Analytical results do not compare well with experimental observations because the natural period considered for the analytical model (based on test shown in Fig. 8(b)) in the short direction is 1.20 s, while that observed during dynamic tests was 0.91 s. This difference could be attributed to difference in fabrication during dynamic and static tests.



(a) Level 3 (PGA = 0.15g)(b) Level 5 (PGA = 0.25g)(c) Level 8 (PGA = 0.40g)

Fig. 10 – Comparison between experimental and analytical response of PSCS specimen in long direction



(a) Level 2 (PGA = 0.10g)   (b) Level 4 (PGA = 0.20g)

Fig. 11 – Comparison between experimental and analytical response of PSCS specimen in short direction

6. Influence of perimeter support conditions

A total of four perimeter support conditions were considered for the horizontal metal frame supporting the plasterboard: 1) free, 2) contact between members of horizontal metal frame and test frame with a coefficient of friction of 0.1, 3) the contact with a coefficient of friction of 0.7, and 4) "linked." Free perimeter support condition refers to horizontal metal frame unsupported at its perimeters. Frictional support conditions were realized through the *singleFPBearing* element by considering an average axial load of 40 N on the 18 bearing elements and the "yield displacement" of 0.1 mm. A very high radius of curvature was assigned to the bearing element so that it would function as a flat slider. "Linked" support condition was realized through a *ZeroLength* element. The element had a lateral stiffness of 64.81 N/mm (see Matale [8]) along the long direction and zero in other directions.

Analyses were performed for the system with four perimeter support conditions subjected to Level 3 shaking (0.15 g) in the long direction. Peak relative displacement between the frame and the horizontal metal frame (and the plasterboard) was 5.2 mm, 0.75 mm, 0 mm and 0.7 mm, respectively, for the four perimeter support conditions. Fig. 12 presents the floor spectra at the plasterboard corresponding to the four perimeter support conditions. Peak floor accelerations corresponding to the four support conditions were 0.27g, 0.15g, 0.18g and 0.31g, respectively. Natural periods at which peak spectral ordinates were observed were 0.35 s, 0.073 s, 0.35 s and 0.10 s, respectively.

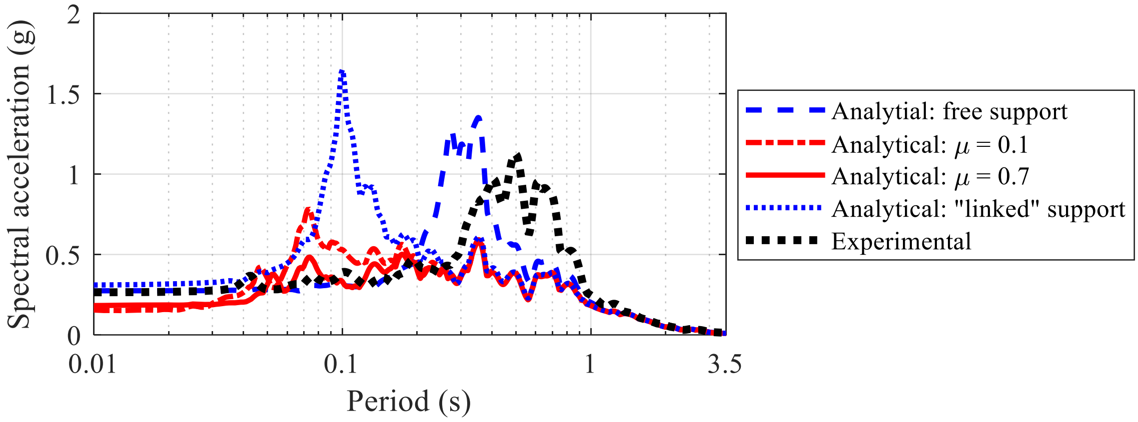


Fig. 12 – Floor spectra of plasterboard with different perimeter support conditions

7. Summary and conclusions

A test set-up comprising of a test frame and a PSCS specimen was subjected to a series of ground motions in the principal horizontal directions. The test frame represents a single-story building and the PSCS specimen is supported by four suspenders connected to the roof of test frame at other ends. Fundamental period of vibration associated with the test frame was approximately 0.05 s in either of the principal horizontal directions, while the fundamental period of vibration associated with the PSCS specimen were 0.3 s and 0.9 s in the two horizontal directions (referred to as “long” and “short” directions, respectively). Damping in the test frame was 1.5% and 1.3%, while that in the PSCS specimen was 6% and 8% in the long and short directions, respectively. The set-up was subjected to ground motions with spectral shape consistent with Indian earthquake standard. Natural period of the PSCS specimen increased with increasing intensity of ground motion to 1.0 s and 1.0 s in the long and short directions, respectively, by the end of experiments. Change in natural period was associated with damage in the lower ends of the suspenders. Moment-rotation relationships for connection between suspenders and roof of the test frame was determined through static tests in long and short directions. An analytical model was developed considering the moment-rotation relationships and non-linear response at the lower ends of the suspenders. The model could capture the natural periods of the system at the beginning of the loading and peak floor accelerations till the intensity level for which an impact was observed between plasterboard and test frame. The model was extended to incorporate three additional support conditions for the PSCS specimen, namely, a contact between horizontal metal frame of the PSCS specimen and test frame with the coefficients of friction of 0.1 and 0.7, and links between horizontal metal frame and test frame. It was found that the relative displacement between horizontal metal frame and test frame reduced substantially when a support at the perimeter was introduced. Peak acceleration associated with the plasterboard and periods at which maximum spectral ordinates changed considerably with a change in perimeter support conditions.

8. Acknowledgements

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9. Copyrights

10. References

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