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SEISMIC PERFORMANCE OF PLASTERBOARD SUSPENDED CEILINGS UNDER SHAKING-TABLE GENERATED MOTIONS

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Abstract

The damage to ceilings during past earthquakes has led to investigations into the performance of ceiling systems and qualify them for various levels of intensity of input motion through shaking table testing. Prescriptive guidelines for design and installation requirements have been proposed from observations of the frequent failure of lay-in tile ceilings. However, for continuous plasterboard systems, the code recommends the engineers to verify the design by experimental testing or use a highly rigid system which connects to all the walls with lateral braces connected to the building diaphragm. In recent earthquakes, some of the failures of continuous plasterboard ceilings have raised questions on the code recommendations and prompted the development of innovative installation schemes.

An experimental study was conducted to study the dynamic behavior and performance of two continuous plasterboard suspended systems, i.e., (a) vertical strut ceiling system with fixed boundaries, and (b) vertical strut ceiling system with free boundaries (25 mm gap). This free boundary system has seismic clip connections similar to the Japanese installation, to connect primary and secondary members. The ceilings were installed in a floor acceleration simulator, which has rigid walls (natural frequency > 17 Hz) and roof (natural frequency ~10 Hz), and this assembly was in turn connected to a uniaxial shaking table and tested along the orthogonal directions, sequentially. The N21E component of the 1952 Kern County earthquake recorded at Taft station was used as shaking table input motion as its response spectrum compares well with the International Building Code (IBC 2015) specified design spectrum.

The experimental study indicated that most of the lateral force is resisted by connections to the perimeter channels for the fixed system, and by clamping and bearing of edge screws in the free system. It was also observed that the cumulative strains developed in the struts of the fixed system were less compared to those of the struts in the free system. The ceiling systems performed well at all the intensities of shaking without any visible damage. However, under sinusoidal excitation at the natural frequency of the test systems, the free boundary system proved vulnerable as it slipped from the perimeter channel leading to major damage. The installation of the vertical strut ceiling system that has free boundaries is vulnerable for multi-storey buildings located in any seismic zone because of its poor performance under large acceleration demands.

Keywords: Nonstructural elements; suspended ceiling; shaking table; seismic qualification; continuous plasterboard

1. Introduction

The two well-known suspended ceiling systems are (a) lay-in-tile system (discrete in nature) and (b) plasterboard system (continuous in nature). The damage to ceilings was not reported until 1964, as the traditional buildings are usually low and rigid compared to the multi-storey buildings [1]. In 1964, Alaska earthquake, the ceiling damage due to building deformations, and the light fixture damage due to the absence of safety wires were reported. The subsequent failures of ceilings occurred during 1966 Gisborne, 1968 Inangahua, 1971 San Fernando, and 1972 Managua (moderate) earthquakes. The extensive damage to ceilings and partitions during the 1972 Managua earthquake convinced the architects and the clients to have resilient ceiling systems. In addition to the existing recommendation of having two adjacent sides connected to wall perimeter in high seismic regions, the Ceiling and Interior System Contractors (CISCA 1972) [2] strengthened the ceilings with hanger wires at the edges and 45-degree sway bracing wires in each direction at 4 meters. The measures proposed by CISCA were later modified and included in ASTM E580-76 (Current edition: ASTM E580/E580M-17 [3]) by adding a vertical strut at the centre of splay (bracing) wires and pop rivets at the wall edges. Even then, there were many a ceiling failure [4, 5, 6] reported during recent earthquakes and the four decades of full-scale shaking table tests [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17] resulted in inconsistent recommendations in using the sway wires and the struts in installation of tile ceilings. However, the past failures resulted in prescriptive guidelines for the design and installation requirements of tile ceiling systems.

The continuous plasterboard ceiling systems are fragile like the tile ceiling systems. These continuous plasterboard ceilings lack even prescriptive guidelines for installation. In the US, the building codes recommend the engineers to verify the design by experimental testing or use a highly rigid system which connects to all the walls with lateral braces connected to the floor/roof. Limited experimental studies were conducted on the plasterboard ceilings having partition walls [18], closely spaced hanger wires [19, 20], no lateral bracings [21], and engineered clip connections [22]. These ceilings performed well for the small areas, however, for the large area ceilings without engineered clip connections damages were found in existing clips and hangers. In the recent earthquakes, some of the failures of continuous plasterboard ceilings in the US [21] and Japan [23] raised questions on the code recommendations and prompted the development of innovative installation schemes to increase their resilience.

In this experimental study, two ceiling systems were tested by replacing a large number of hanger wires with limited vertical angular struts for fully fixed (no relative movement) and free (to accommodate demand displacements) systems. To accommodate these ceiling systems and to impart the floor accelerations to ceilings as input at their attachment points, a floor acceleration simulator/ test frame has been modelled in SAP2000 [24] and constructed in Structural Engineering Laboratory at IIT Kanpur.

2. Details of the Ceiling Systems

Two ceiling systems were considered for the full-scale shaking table tests. These two systems are (1) vertical strut suspended ceiling system with fixed boundaries (AFX_S) (2) vertical strut suspended ceiling system with free boundaries (AFR_S). The system which has the free boundaries is assumed to accommodate the demand displacements of the ceiling during seismic excitation. These two ceiling systems have different configurations and installation procedures with the components and spacing as given in Table 1. The plan area of the ceiling is 2415 mm × 2975 mm and is attached to the floor acceleration simulator/test frame at the height of 2.4 m from the column base. Wooden ledges were added to the test frame at the level of the ceiling to achieve various boundary conditions for the ceiling systems.

2.1 Vertical strut suspended ceiling system with fixed boundaries (AFX_S)

In this ceiling system AFX_S (Fig. 1a), the ceiling sections act as secondary members and the intermediate channels act as primary members. The fixed conditions around the perimeter were physically modelled by connecting the ceiling sections to the longwall perimeter channel through metal to metal screws, as shown in Fig. 1d. The intermediate channel section was connected to the shortwall wooden ledge through soffit cleat and nut and bolt arrangement, as shown in Fig. 1e. The whole ceiling system was suspended from the roof of the test frame by six struts (S1 to S6). The longer legs of the struts were positioned along the longwall of the test frame. One end of the strut connected to the intermediate channel through two metal to metal screws (Fig. 1f) and the other end connected to the roof through soffit cleat and nut and bolt arrangement (Fig. 1g). The plasterboard panels were attached to the underside of the ceiling sections (Fig. 1h) and the bottom flange of perimeter channels (Fig. 1i) through drywall screws. The physical model of the test system AFX_S for the shaking table testing is shown in Fig. 1b & 1c.

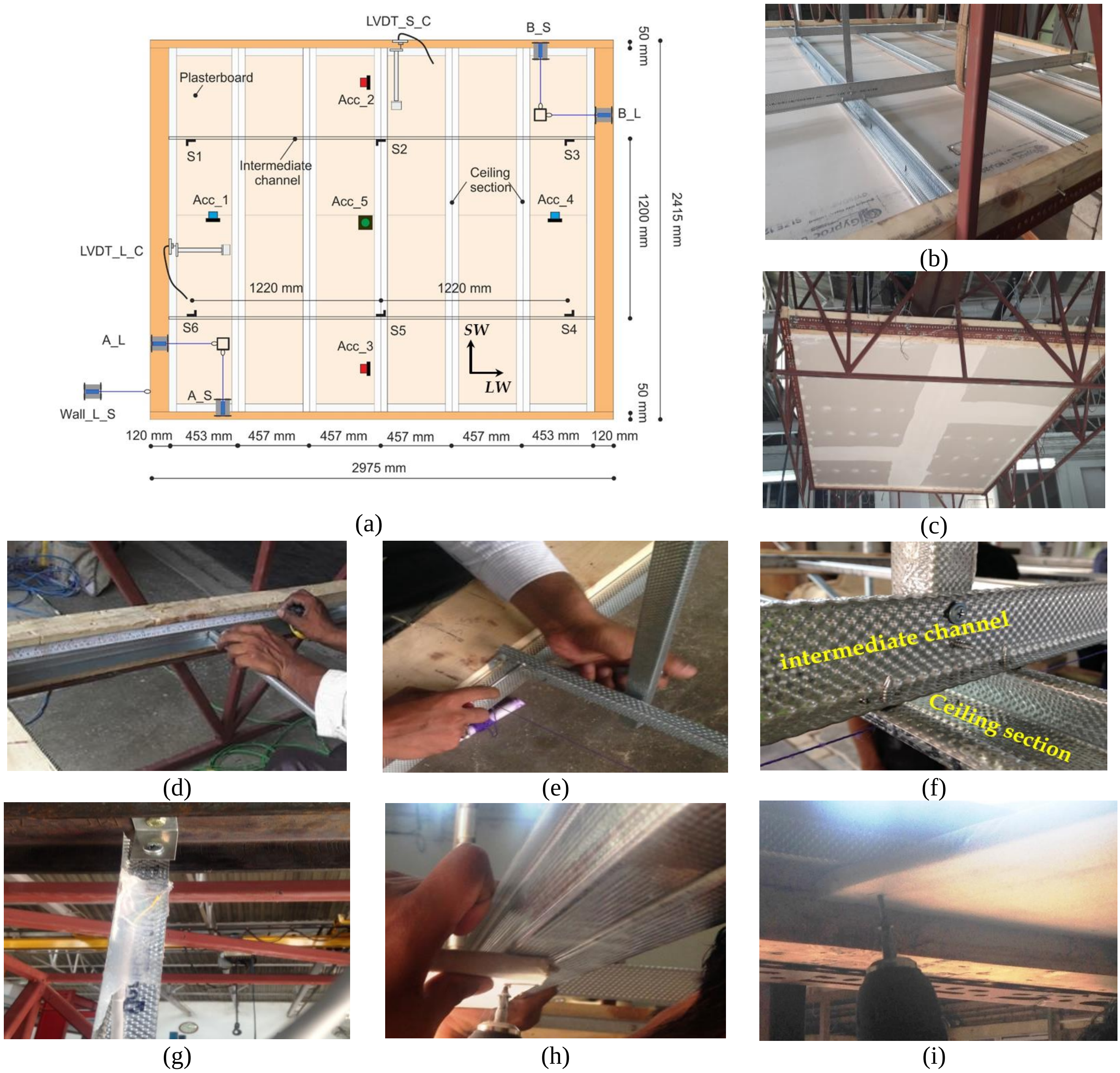
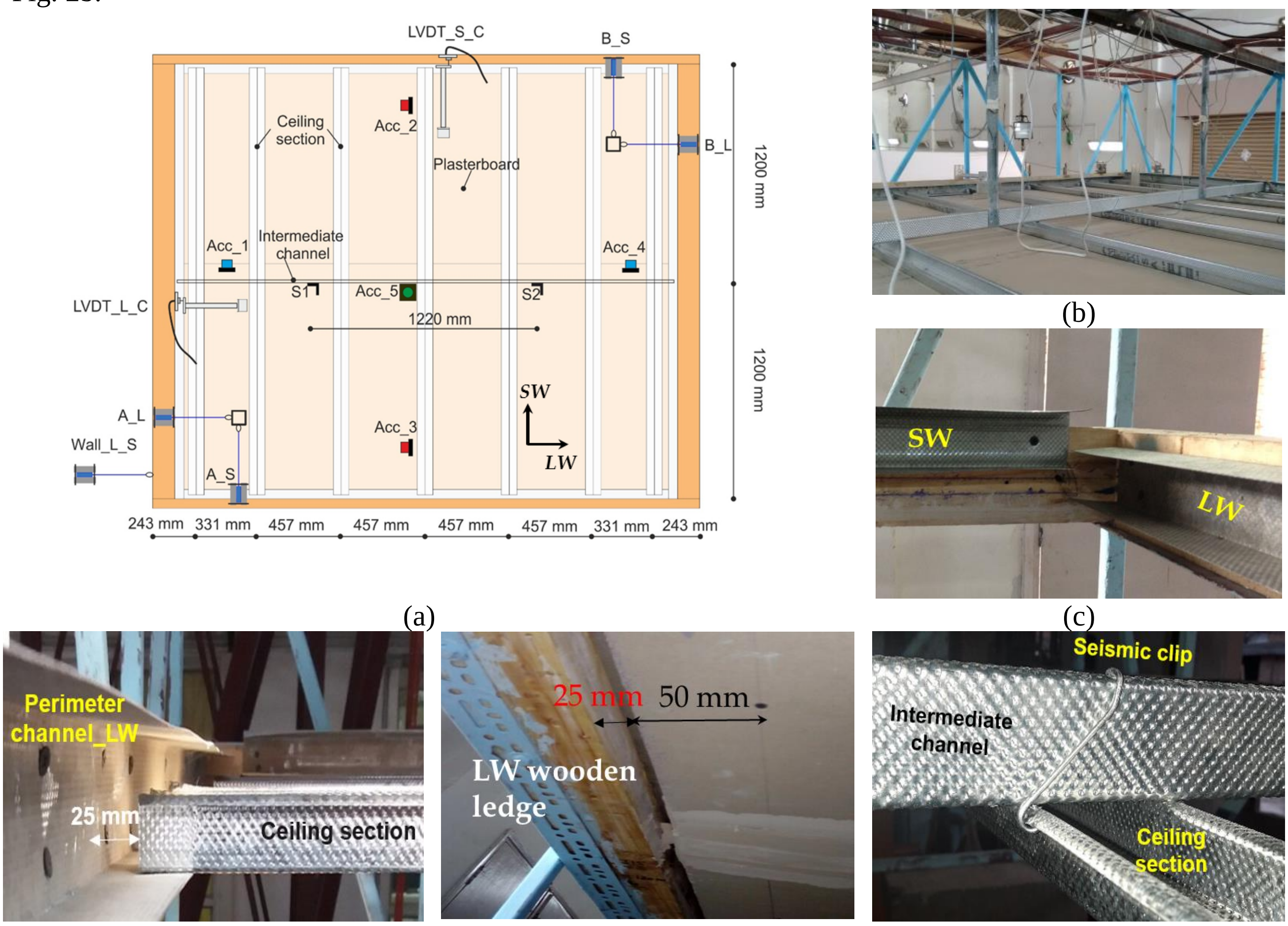


Fig. 1 – (a) Plan view of ceiling system AFX_S (b), (c) installed ceiling system AFX_S for the shaking table test (d) positioning of ceiling sections and connection with perimeter channel (e) intermediate channel connected to SW wooden ledge through soffit cleat and nut and bolt arrangement (f) intermediate channel to strut and ceiling section connection (g) strut to roof connection (h) plasterboard to ceiling section connection (i) plasterboard to perimeter channel flange connection

2.2 Vertical strut suspended ceiling system with free boundaries (AFR$_S$)

The ceiling system AFR$_S$ (Fig. 2a) was modelled physically to understand the effect of free boundaries on the performance of the plasterboard ceilings. In contrast to the same elevation of perimeter channels in system AFX$_S$, there is a level difference of 50 mm (SW perimeter channel above the LW channel) between the perimeter channels, as shown in Fig. 2c. A gap of 25 mm was left all around the ceiling perimeter to accommodate the displacement demands during earthquake motion, as shown in Fig. 2d. In this system, there is no positive connection between the ceiling sections and the perimeter channels. The perimeter channel flange was sandwiched (clamping) between the plasterboard and ceiling section by a drywall screw positioned at 50 mm from the plasterboard edge, as shown in Fig. 2e. Clamping and bearing of the screws were considered effective in resisting the movement of the ceiling system when the vibration is along LW and SW directions, respectively. Seismic clips have been used to connect the ceiling sections and the intermediate channel (similar to Japanese ceiling system clips connecting the primary and secondary members) as shown in Fig. 2f. The complete system suspended from the roof of the test frame by only two struts placed along LW direction and on the intermediate channel. The strut to the roof and intermediate channel connections are the same as that of the system AFX$_S$, however, the struts in AFR$_S$ didn't have the knurling on their surface. The physical model of the free system AFR$_S$ for the shaking table tests is shown in Fig. 2b.



(a) (b) (c) (d) (e) (f)

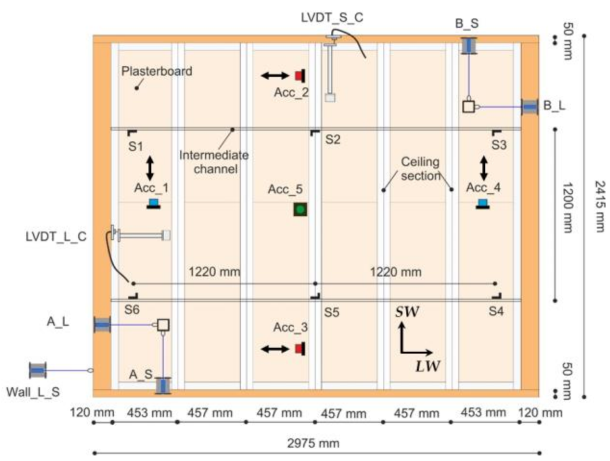
Fig. 2 – (a) Plan view of ceiling system AFR$_S$ (b) installed ceiling system AFR$_S$ for the shaking table test (c) level difference between LW and SW perimeter channels (d) positioning of ceiling sections and 25 mm gap with perimeter channel (e) drywall screw positioned at 50 mm from the LW plasterboard edge (f) seismic clip connecting ceiling section and intermediate channel

Table 1 – Components in ceiling systems

Component	Dimensions (mm)	Quantity and/or c/c spacing	
		Ceiling system AFX$_S$	Ceiling system AFR$_S$
Ceiling section	80 × 26 × 52 × 0.5	5 nos. @ 457 mm	5 nos. @ 457 mm 2 nos. @ 331 mm
Intermediate channel	15 × 45 × 15 × 0.9	2 nos. @ 1200 mm_SW	1 nos. @ centre
Strut (Type 1)	25 × 10 × 0.5 (knurling)	6 nos. @ 1220 mm_LW @ 1200 mm_SW	–
Strut (Type 2)	25 × 25 × 0.5 (no knurling)	–	2 nos. @ 1220 mm_LW
Plasterboard	12.5 mm thick	12.5 mm thick	12.5 mm thick
Perimeter channel (Type 1)	20 × 28 × 30 × 0.5	2 nos. along LW 2 nos. along SW	–
Perimeter channel (Type 2)	50 × 50 × 50 × 0.5	–	2 nos. along LW 2 nos. along SW
Seismic clip	2.46 mm diameter	–	5 nos. @ 457 mm 2 nos. @ 331 mm

3. Instrumentation and Loading Protocol

The ceiling systems were instrumented with five uniaxial accelerometers (strain gauge based; range: ± 10 g), two of each oriented along the long and shortwall, and one at the center of the ceiling to record the vertical vibrations due to horizontal excitations as shown in Fig. 3. Three accelerometers were placed on the roof of the test frame to measure the floor accelerations input to the ceiling system through the points of attachments (strut to roof connection). One reference accelerometer was attached to the base of the shake table to measure the acceleration input to the test frame. The acceleration spectrum of this acceleration record (spectral accelerations) was compared with the IBC 2015 [25] spectrum using one-sixth octave frequency ordinate values. Each strut was instrumented with four strain gauges, keeping the long leg of the strut along the LW direction of the ceiling system. The test systems were also instrumented with LVDTs (range: ±50 mm) and wire potentiometers (range: ± 540 mm) to measure the in-plane displacements of the ceilings and the test frame.



Accelerometers:
Acc_1; Acc_2; Acc_3; Acc_4; Acc_5

LVDTs:
LVDT_L_C; LVDT_S_C

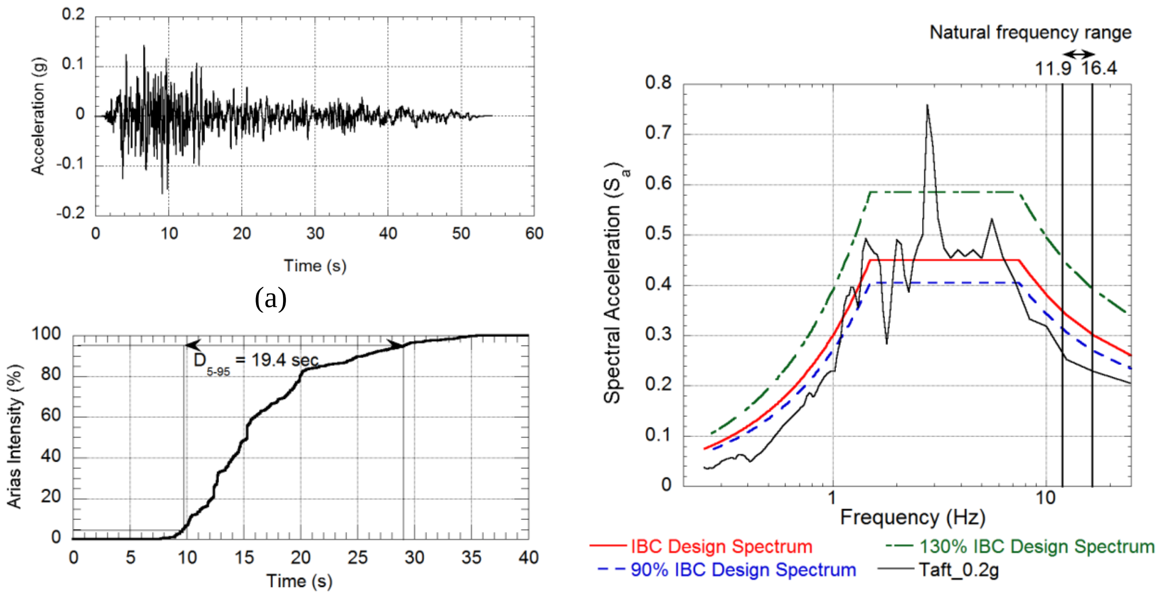
Wire potentiometers (wire pots):
A_L; B_L

A_S; B_S

Wall_L_S

Fig. 3 – Location of accelerometers, LVDTs, and wire potentiometers at ceiling level

The performance of the ceiling systems was verified by installing them in the test frame and testing them under shaking table generated motions. The installed suspended ceiling performance can be considered adequate for a zone if it sustains the largest imposed accelerations derived for that zone and fails its purpose for a higher zone. This can be achieved by testing the ceiling system for various levels of intensity of input motion similar to an incremental dynamic analysis [26]. The ICC ES AC156 [27] recommends using the ground motion whose floor response spectrum envelops the horizontal spectra mentioned, and many researchers considered this motion for the shaking table tests. However, these synthetic motion characteristics deviate largely from the real ground motion characteristics. In the present study, for the performance evaluation of plasterboard ceilings, the N21E component of the 1952 Kern County earthquake recorded at Taft station (Fig. 4a) was used as a ground motion for the shaking table acceleration runs. This ground motion's response spectrum compares with the IBC 2015 design spectrum to be considered at the base of a structure, as shown in Fig. 4c. Only the first 30 s of Taft motion was considered as input motion to the shaking table and the Husid plot in Fig. 4b shows that the strong motion shaking for a duration (time estimated between 5 and 95 percent (DS_{5-95}) of the Arias intensity) of 19.4 s meets the AC 156 requirement of 20 s.



(b) (c)

Fig. 4 – (a) N21E component of the 1952 Kern County earthquake (Taft 1952) (b) Husid plot (c) comparison of IBC design spectrum with Taft 0.2g spectrum

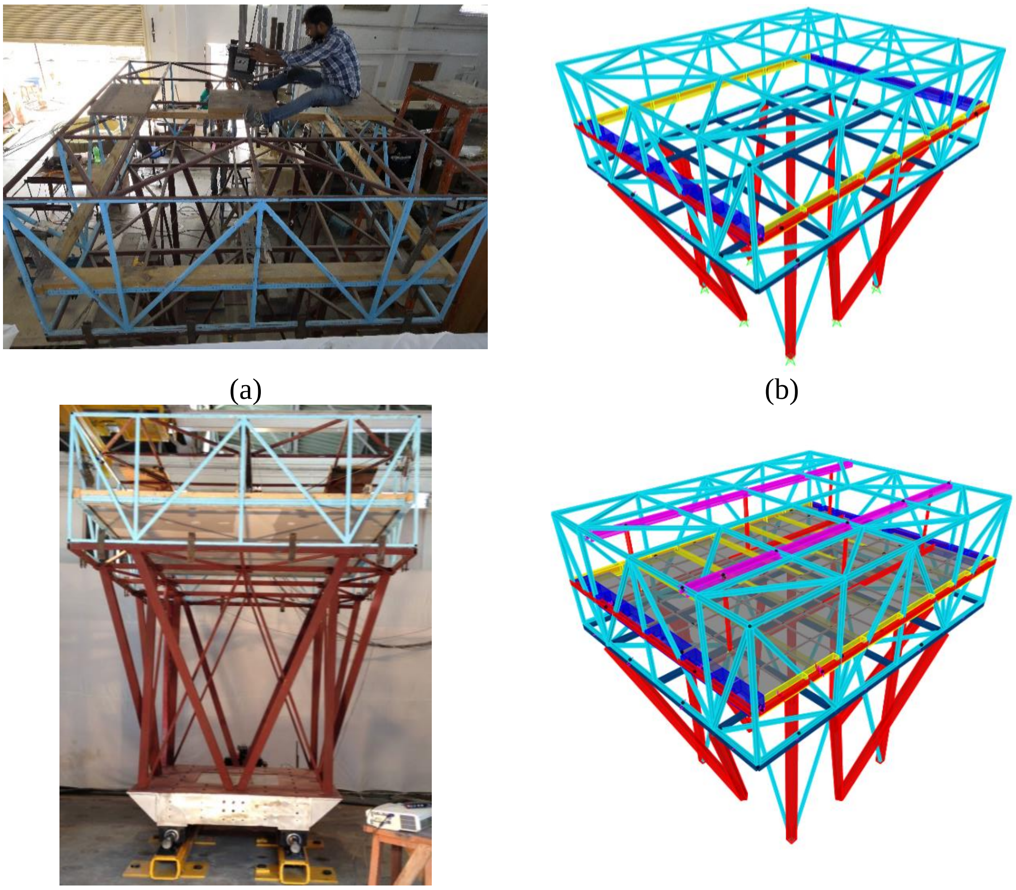
This Taft motion has been scaled to derive eleven levels of input intensities i.e., Level_1 to Level_11 (0.05g, 0.1g, 0.15g, 0.2g, 0.25g, 0.3g, 0.35g, 0.4g, 0.5g, 0.6g, and 0.7g PGAs'). For the uniaxial shaking table, after applying an input motion in a direction (either LW or SW), the test system was rotated to test it in the orthogonal direction. This procedure has been followed until the failure of the ceiling system. In between the seismic test runs, white noise tests have been conducted to detect the damage (loosening of connections, breaking of plasterboards, yielding of members, etc.).

4. Dynamic Characterization

The dynamic characteristics of the test frame and the ceiling systems were evaluated along the longwall, shortwall and vertical directions from the free vibration (impact hammer), forced vibration (linear mass shaker, white noise test, or both) tests, or both. The linear mass shaker (a long stroke, electrodynamic force generator Electro-Seis make, model APS 113) was placed on the roof of the test frame and excited with the harmonic sine sweep to find its resonance frequencies. The white noise tests were conducted using the servo hydraulic-driven uni-axial shaking table [28] to evaluate the resonance frequencies.

4.1 Test frame (Floor acceleration simulator)

The test frame with the installed ceiling system for the shaking table testing and their analytical models developed in SAP2000 are shown in Fig. 5. The test frame's natural and resonant frequencies were evaluated from free vibration using impact hammer and forced vibration using liner mass shaker (Fig. 5a), respectively. The experimentally evaluated natural frequencies of the test frame were analytically verified from the modal analysis are shown in Table 2.



(a) (b)

(c) (d)

Fig. 5 – (a) Linear mass shaker on the roof of test frame (b) analytical model of test frame (c) ceiling system AFX_S on the shaking table (d) analytical model of ceiling system AFX_S

Table 2 – Experimentally and analytically evaluated natural frequencies of the test frame

Direction	**Natural frequencies of the test frame**		
	Experiment, Hz		**Analytical, Hz**
	Free	**Forced**	
Longwall	22.89	22.84	21.94
Shortwall	20.01	20.99	20.46
Vertical	15.59	15.05	15.16
Torsion	20.87	21.05	21.01

4.2 Test ceiling systems

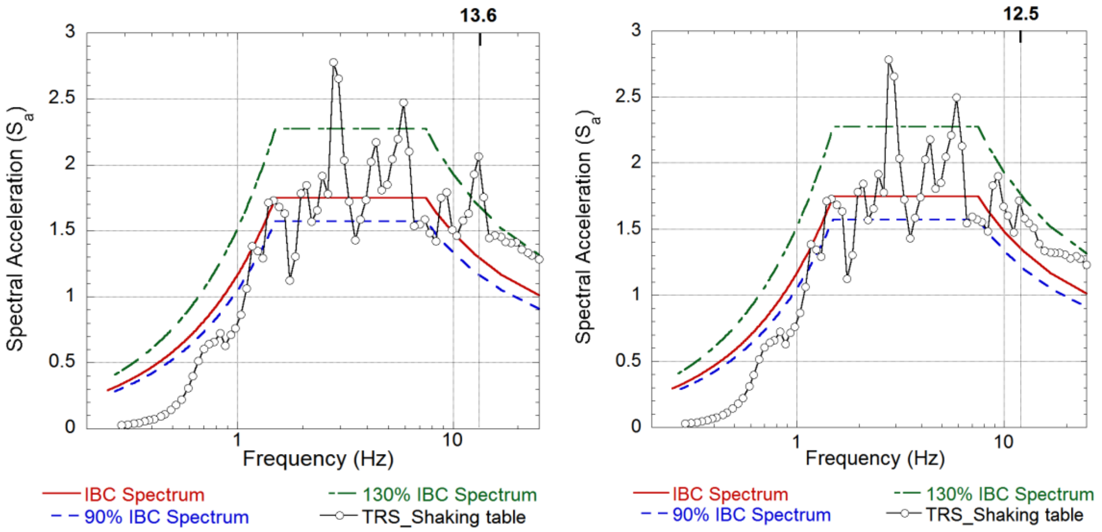
The dynamic characteristics of the test systems were evaluated from the free vibration and low amplitude white noise (0.045g) shaking table inputs along the long and shortwall directions, individually. The response analysis of the ceiling and the roof indicate that the ceiling systems vibrated along with the test frame leading to the same natural frequencies along the horizontal, vertical, and torsional directions. The natural frequencies, and resonant frequencies and damping values (white noise) evaluated for systems AFX_S and AFR_S are given in Table 3.

Table 3 – Test systems natural and resonant frequencies and damping

Direction	Test system AFX_S			Test system AFR_S		
	Natural freq Hz	**Resonant freq Hz**	**Damping**	**Natural freq Hz**	**Resonant freq Hz**	**Damping**
Longwall	15.00	14.09	1.16%	16.36	14.03	1.85%
Shortwall	13.00	12.73	0.33%	13.31	12.79	0.35%
Vertical	12.00	12.00	-	11.93	11.93	-
Torsion	20.20	20.06	-	20.14	20.10	-

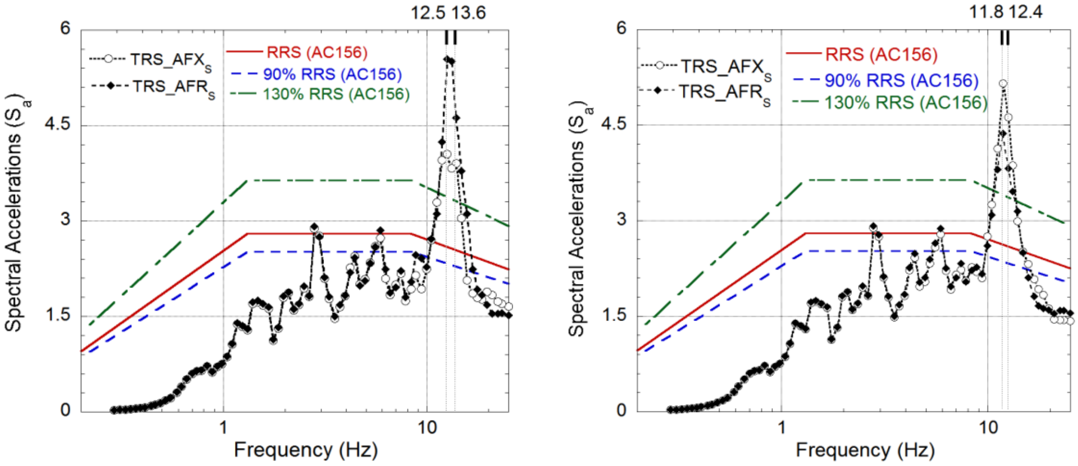
5. Observed Behaviour

The ceiling systems AFX_S and AFR_S were subjected to eleven levels of ground motions along the long and shortwall directions. The response of the accelerometer at the base of the shaking table (table response spectrum: TRS_Shaking table) overlaps the IBC spectrum defined for a particular level of intensity, here, it is shown for the Level_11 motion of the test system AFX_S (Fig. 6). The recorded responses (test response spectrum) at the roof level of system AFX_S and AFR_S have been compared with the AC156 proposed horizontal required response spectrum (RRS) for floor/roof at the octave frequencies is shown in Fig. 7. Fig. 7a & 7b shows that the supplied input motion was filtered and amplified at the resonance frequency of the test system along the long and shortwall directions, respectively.



(a) (b)

Fig. 6 – IBC spectrum vs table response spectrum (TRS_Shaking table) for (a) L11_LW (b) L11_SW of test system AFX_S

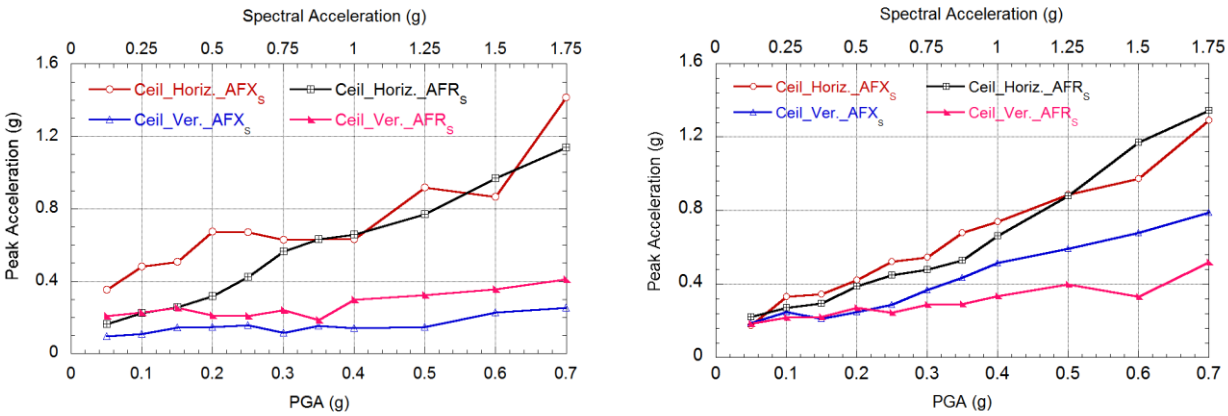


(a) (b)

Fig. 7 – AC156 required response spectrum (RRS) vs test response spectrum (TRS) for the roof of test system AFX_S and AFR_S along (a) long and (b) shortwall directions

The horizontal and vertical accelerations at the ceiling level of AFX_S and AFR_S have been recorded and their peak values are plotted against the input ground motion PGA values (and spectrum values) as shown in Fig 8. The ceiling system AFX_S which was fixed all around had sustained large horizontal accelerations when tested along LW and SW directions. This system has one intermediate channel and three struts on either side of the centre line (at 600 mm and near edges along SW) created a flexible module at the centre and a rigid module at the edges of the ceiling system. This characteristic of the ceiling system AFX_S led to record small vertical accelerations when tested along LW and large vertical accelerations when tested along SW.

The ceiling system AFR_S sustained large horizontal acceleration along SW direction due to the bearing strength of the drywall screw connection. On the other hand, the weak clamping force has led to record small accelerations when tested along the LW direction. The vertical accelerations recorded in AFR_S along LW are large due to the centrally placed intermediate channel and vertical struts. However, the absence of vertical restraints at the edges led to record small vertical accelerations when tested along the SW direction. It was also physically observed that the corners of the plasterboard oscillated vigorously when the system AFR_S tested along the LW direction.



(a) (b)

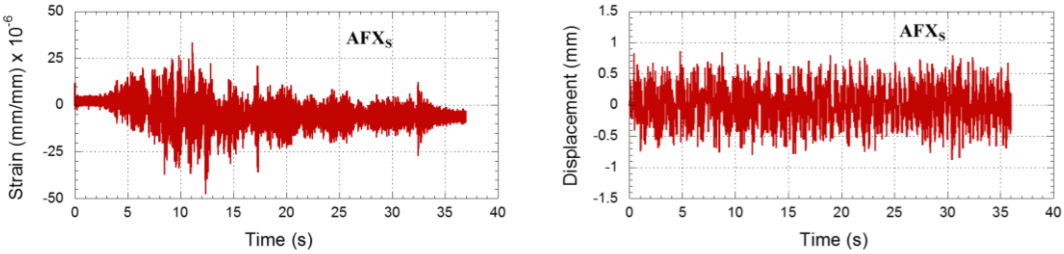
Fig. 8 – Comparison of peak horizontal and vertical accelerations of ceiling systems AFX_S and AFR_S for the seismic test runs along (a) long and (b) shortwall directions

On comparing, the system AFR_S displaced within the gap provided (25 mm) and recorded relatively small accelerations than AFX_S, when tested along the LW and SW directions. The flexible module of AFX_S

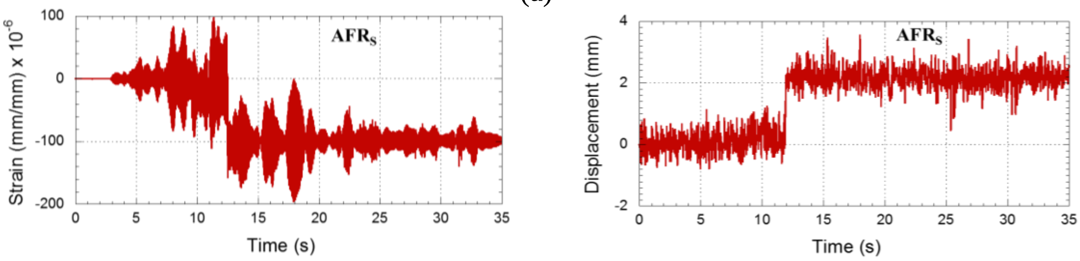
and rigid module of AFR$_S$ at the centre of the ceiling resulted in small and large vertical accelerations, respectively when tested along LW direction. However, the flexible module of AFR$_S$ and the rigid module of AFX$_S$ at the edges of the ceilings resulted in small and large accelerations, respectively when tested along the SW direction.

The peak strain and displacement responses of systems AFX$_S$ and AFR$_S$ are presented in Fig. 9 for the Level_11 input motion along LW direction. For this input motion, the system AFX$_S$ showed approximately 1 mm displacement and a peak strain of about 50 microstrains on a strut (cumulative: 400 microstrains). At the same level of input motion, the system AFR$_S$ showed a displacement of plasterboard about 4 mm, and a peak strain of 200 microstrains on a strut (cumulative: 600 microstrains). The AFX$_S$ fixed connections to the perimeter channel played a major role in resisting the induced inertial forces, thereby experiencing smaller displacement and stain demands on ceiling and struts, respectively. However, the clamping force developed by edge screws in AFR$_S$ was ineffective in completely resisting the inertial forces developed at the ceiling system, resulted in large displacement and strain demands in the ceiling and struts, respectively.

Both the ceiling systems performed well during all the seismic test runs, and as the test continued to verify their performance till failure, an extreme dynamic loading (sinusoidal excitation) applied at their LW natural frequencies (for AFX$_S$:15 Hz; for AFR$_S$:16.36 Hz). The system AFX$_S$ remained intact with no visible damage but the system AFR$_S$ suffered major damage as shown in Fig. 10 i.e., ceiling sections slipped from the perimeter channels. The AFR$_S$ system proved to be vulnerable under large acceleration demands, and therefore installation in multi-storey buildings located in any seismic zone should be avoided.



(a)



(b)

Fig. 9 – Strain and displacement response of ceiling system (a) AFX$_S$ and (b) AFR$_S$ at Level_11 input motion along LW direction

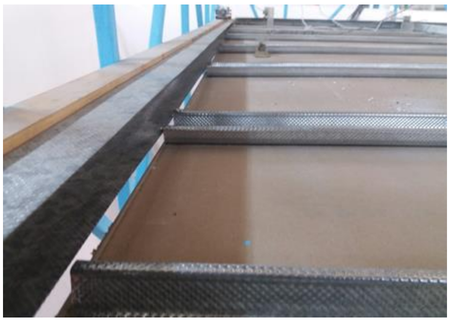


Fig. 10 – Slip of ceiling sections from the perimeter channel

6. Conclusions

This experimental study is concerned with the performance evaluation of two continuous plasterboard suspended systems, i.e., vertical strut ceiling system with fixed boundaries, and vertical strut ceiling system with free boundaries and having a gap of 25 mm around the perimeter. The ceiling systems were installed in the test frame similar to the field installation, and the dynamic characteristics of the test systems were evaluated from the free and forced vibration tests. The test ceiling systems were subjected to increasing levels of ground motions up to 0.7g and observed large displacement demands in a system that had all edges free. The experimental results indicate that most of the lateral force is resisted by connections to the perimeter channels in the fixed system, and by clamping and bearing of edge screw in the free system. The cumulative strains developed in the struts of the free boundary ceiling system were large compared to those of the struts in the fixed system.

The system with fixed edges experienced no damages for all the levels of input motions and also at extreme dynamic loading (sinusoidal excitation at natural frequencies). The system with free edges performed well for all the seismic test runs, but under extreme dynamic loading, the ceiling sections slipped from the perimeter channels leading to severe damage. In addition, the seismic clips were found effective (no damage found) and behaved similar to metal to metal screws. The installation of a vertical strut ceiling system that has free boundaries is vulnerable for multi-storey buildings located in any seismic zone because of its poor performance under large acceleration demands.

7. Acknowledgements

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8. References

[1] Clark WD, Glogau OA (1979): Suspended ceilings: The seismic hazard and damage problem and some practical solutions. *2nd South Pacific Regional Conference on Earthquake Engineering*, Wellington, New Zealand.

[2] Ceiling and Interior System Contractors (CISCA) (1972): Seismic restraint of direct hung suspended ceiling assemblies, Chicago.

[3] ASTM International E580/E580M-17 (2017): Standard practice for installation of ceiling suspension systems for acoustical tile and lay-in panels in areas subject to earthquake ground motions, West Conshohocken, USA.

[4] MacRae GA, Lehman D (2001): Chapter 4, Buildings, in The Nisqually Washington earthquake. *Preliminary Reconnaissance Report* co-authored by the Nisqually Earthquake Clearinghouse Group, Earthquake Engineering Research Institute, Seattle, USA.

[5] Masato M, Mitsujib K (2012): Building damage during the 2011 off the Pacific coast of Tohoku earthquake. *Journal of Soils and Foundations*, **52** (5), 929–944.

[6] Dhakal RP (2010): Damage to non-structural components and contents in 2010 Darfield earthquake. *Bulletin of the New Zealand Society for Earthquake Engineering*, **43** (4), 404-411.

[7] ANCO (1983): Seismic hazard assessment of nonstructural ceiling components. *NSF Rep. No. CEE-8114155*, Culver City, USA.

[8] Rihal SS, Granneman G (1984): Experimental investigation of the dynamic behaviour of building partitions and suspended ceilings during earthquakes. *Rep. No. ARCE R84-1*, California Polytechnic State University, Pomona, USA.

[9] Yao GC (2000): Seismic Performance of direct hung suspended ceiling systems. *Journal of Architectural Engineering*, **6** (1), 6–11.

[10] Badillo-Almaraz H, Whittaker AS, Reinhorn, AM (2007): Seismic fragility of suspended ceiling systems. *Earthquake Spectra*, **23** (1), 21-40.

[11] Gilani AS, Glasgow B, Ingratta T (2008): Seismic performance of directly hung suspended ceilings with engineered perimeter product. *14th World Conference on Earthquake Engineering*, Beijing, China.

[12] Echevarria A, Zaghi AE, Soroushian S, Maragakis M (2012): Seismic fragility of suspended ceiling systems. *15th World Conference on Earthquake Engineering*, Lisbon, Portugal.

[13] Rahmanishamsi E, Soroushian S, Maragakis M (2014): System-level experiments on ceiling/piping/partition systems at UNR-NEES site. *10th U.S. National Conference on Earthquake Engineering*, Alaska, USA.

[14] Robson MJ, Kho D, Pourali BA, Dhakal RP (2014): Feasibility of a fully floating ceiling system. *NZSEE Annual Conference*, Auckland, New Zealand.

[15] Soroushian S, Ryan KL, Maragakis M, Sato E, Sasaki T, Okazaki T, Tedesco L, Zaghi AE, Mosqueda G, Alvarez D (2012): Seismic response of ceiling/sprinkler piping nonstructural systems in NEES TIPS/NEES Nonstructural/NIED collaborative tests on a full scale 5-story building. *43rd Structures Congress*, ASCE, Chicago, USA.

[16] Pourali A, Dhakal RP, MacRae GA, Tasligedik AS (2015): Shake table tests of perimeter-fixed type suspended ceilings. *New Zealand Society for Earthquake Engineering Annual Technical Conference*, Rotorua, New Zealand.

[17] Pourali A, Dhakal RP, MacRae G, Tasligedik AS (2017): Fully floating suspended ceiling system: experimental evaluation of structural feasibility and challenges. *Earthquake Spectra*, **33** (4), 1627-1654.

[18] McCormick J, Matsuoka Y, Pan P, Nakashima M (2008): Evaluation of non-structural partition walls and suspended ceiling systems through a shake table study. *Structures Congress: Crossing Borders*, Vancouver, Canada.

[19] Magliulo G, Pentangelo V, Maddaloni G, Capozzi V, Petrone C, Lopez P, Talamonti R, Manfredi G (2012): Shake table tests for seismic assessment of suspended continuous ceilings, *Bulletin of Earthquake Engineering*, **10** (6), 1819–1832.

[20] Magliulo G, Petrone C, Capozzi V, Maddaloni G, Lopez P, Manfredi G (2014): Seismic performance evaluation of plasterboard partitions via shake table tests. *Bulletin of Earthquake Engineering*, **12** (4), 1657-1677.

[21] Gilani AS, Takhirov SM, Straight Y (2015): Seismic evaluation of drywall suspended ceilings using shake table testing and the finite element analysis. *Improving the Seismic Performance of Existing Buildings and Other Structures*, San Francisco, USA.

[22] Watakabe M, Inai S, Ishioka T, Iizuka S, Takai S, Kanagawa M (2012): A study on the behavior of seismically engineered ceiling systems of large open structures subjected to earthquake excitations. *15th World Conference on Earthquake Engineering*, Lisbon, Portugal.

[23] Motoyui S, Satoh Y, Kawanishi T (2010): Dynamic characteristics of a Japanese-style ceiling. *7th CUEE and 5th ICEE Joint Conference*, Tokyo, Japan.

[24] CSI, SAP2000: Integrated software for structural analysis and design. Computers and Structures Inc., Berkeley, USA.

[25] IBC (2015). International building code. Washington, DC, USA.

[26] Vamvatsikos D, Cornell CA (2002): Incremental dynamic analysis. *Earthquake Engineering & Structural Dynamics*, **31** (3), 491-514.

[27] ICC-ES AC156 (2010): Acceptance criteria for the seismic certification by shake-table testing of non-structural components, International Code Council Evaluation Service, Whittier, USA.

[28] Sinha P, Rai DC (2009): Development and performance of single-axis shake table for earthquake simulation. *Current Science*, **96**, 1611-1620.

