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EVALUATION OF SEISMIC PERFORMANCE OF SUSPENDED CEILING SYSTEMS USING DYNAMIC TESTING AND FINITE ELEMENT ANALYSIS

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Abstract

In recent earthquakes, suspended ceilings have experienced widespread extensive damage. Such failure resulted in life-safety hazard, blocking of egress, and financial losses due to damage and business interruption. To address such vulnerability, new and strict seismic design and installation requirements were introduced in the building codes staring with the UBC 1997. Starting in 2000's, shake table testing of suspended ceiling systems have been undertaken by all major manufacturers in the US, followed by a recently-completed large scale testing in both the US and Japan to investigate the response of ceilings as part of the building environment. Independently, testing and evaluation of suspended ceilings have been underway by the authors in the past several years. This paper presents the results from static and cyclic testing of ceiling perimeter installation. The perimeter attachments are one of the key elements determining the overall system response. In addition, manufacturers have developed proprietary seismic clip attachments as substitute for the code-prescribed installation. The tests have been completed and the capacity data were used to assess the efficacy of the alternate connections and to correlate the member capacities with the demand computed from shake table testing of full-scale systems and with the prescriptive requirements of the building code.

Keywords: Suspended ceilings shake table testing, seismic qualification, cyclic testing, and finite element analysis

1 Introduction

Suspended ceilings are a main feature of modern buildings. There are two distinct types of suspended ceilings. For both systems, first the grid (comprised main runners spanning in one direction, and cross tees spanning in the orthogonal direction and framing into the main runners) is assembled. The grids are suspended for the structure by means of hanger wires. For the lay-in panel suspended ceilings (LPSC), the panels are then placed above the grid and in the modules created by the grid components. There is no direct mechanical connection between the panels and the gird or between the panels and the perimeter molding. For the dry wall suspended ceilings (DWSC), sheets of drywall are placed below the grid and are directly attached to both the perimeter trim and the grid members using screws. Fig. 1 and Fig. 2 present schematics of the two types of ceilings.

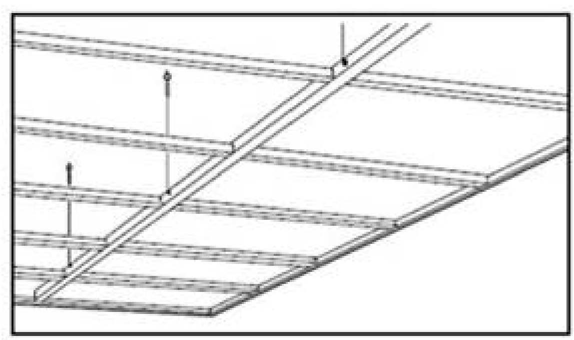


Fig. 1 LPSC

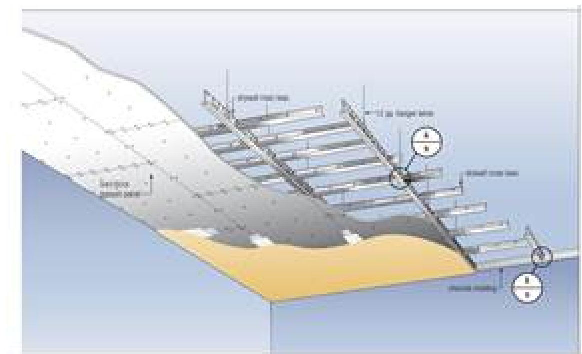


Fig. 2 DWSC (US)

Given the differences in installation, it is anticipated that these two types of systems would have somewhat of different design requirements and seismic performance. For example, for the LPSC, the panels are free to move within the modules and are cut short, whereas, for the DWSC, the drywall panel serves as a diaphragm connecting the ceiling members together. Furthermore, for the LPSC, the ceiling system is unattached to at least two adjacent sides of the building, whereas, for the DWSC, the panels are screwed to the structure on all four sides. Therefore, for the LPSC, the motion of the ceiling system is to some extent independent of the building, while for the DWSC, the ceiling system would experience the same motion as the building. As a result, the LPSC response can be classified more dependent on acceleration, while DWSC performance would depend more on the drift of the attached building.

2 Building Code Provisions

Design codes have incorporated specific design and installation criteria for LPSC systems. For example, in the US the building code [1] requires that the grid connections have a minimum capacity of 800 N, hanger wires spaced at 1.2 m and have a minimum capacity of 450 N. In addition, installation requirements for the attachment of the grid elements to perimeter angles mounted to the walls in the building rooms are specified. In the US, the code recognizes the different construction and installation of the DWSC and as such, it writes: *Suspended ceilings constructed of screw- or nail-attached gypsum board on one level that are surrounded by and connected to walls or soffits that are laterally braced to the structure above are exempt from the requirements of this section.*

Ceiling construction and code's prescriptive requirements vary in other countries. For example, in New Zealand, the seismic code [2] has much less prescriptive requirements for suspended ceilings—either LPSC referred to as two-way exposed grid or DWSC, known as screw fixed plasterboard. Instead, the code charges the design engineer and ceiling manufacturer with ensuring that the ceiling design and installation are satisfactory. In Japan, DWSC are typically constructed by attaching panels to cross furring in one direction. The furring are then connected to channels (main runners) spanning in the orthogonal direction and to the structure above via U-shaped clips [3]. Give that the design for DWSC in Japan is quite different from the US, it is not anticipated that the two systems would have similar performance.

2.1 Past Seismic Performance

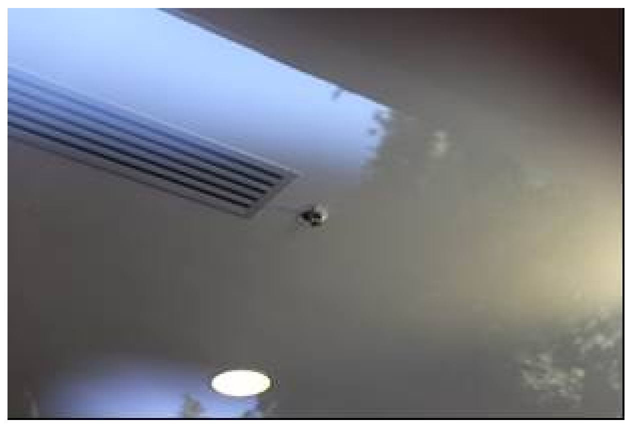
In the US, LPSC systems have performed poorly during past earthquakes, leading to blocking of egress, financial losses, and business interruptions. The damage to LPSC systems have been widespread and have occurred in moderate earthquakes. Following the recent earthquakes, the US building codes have implemented prescriptive design and installation requirements. By contrast, there have not been reports of damage to the DWSC in the US in the past earthquakes.

Examples of damage to LPSC is shown in Figure 3 in a commercial building during the 2014 Napa (CA) Earthquake. By contrast, there was little damage to a DWSC in a department store. During the earthquake, displacements of the sprinkler system exceeded the code prescribed clearance between the ceiling and the sprinkler, causing a local tear in the panel. Nevertheless, the structural integrity of the DWSC as a whole was preserved.

In New Zealand, there was significant damage to the LPSC systems after the 2010 and 2011 earthquakes in Christchurch ([12] and [13]). It is difficult to correlate the damage to LPSC systems in New Zealand to the US, given that there are fewer prescriptive installation requirements in New Zealand. Figure 3 presents an example of damage following the 20111 Earthquake. It is also noted that the authors of New Zealand report noted that the DWSC types are not common in New Zealand and they did not provide evidence of damage.

One of the most specular failures of DWSC system has occurred in Japan (Motoyui and Kawanishi 2010); see Figure 3. However, as it was previously noted, the main cause of the failure is the use of special attachment in Japan, which is not common in the US.[1]

LPSC 2014 Napa Earthquake



DWSC 2014 Napa Earthquake

LPSC, 2011 New Zealand (Rajesh et al 2011)

DWSC , (Motoyui,, and Kawanishi 2010)

Fig. 3 Past failures of suspended ceilings

[1] It is noted that the DWSC construction in the US and Japan are not similar

3 Seismic certification by means of shake table testing

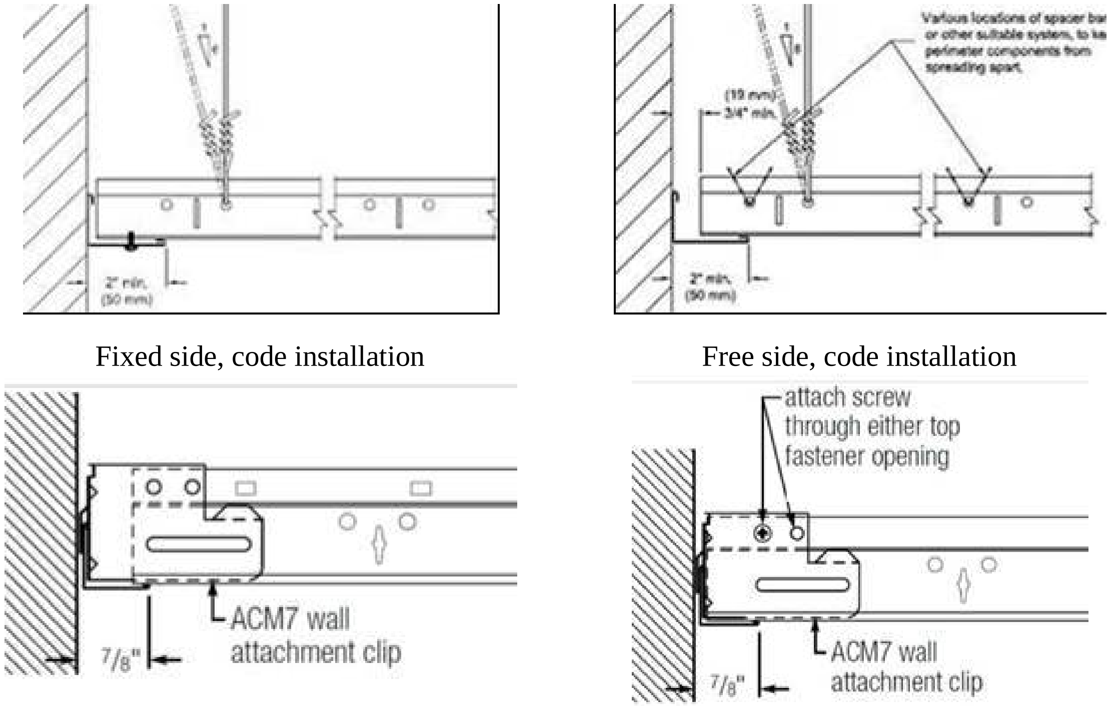
3.1 Overview

In the US, the seismic force acting on the suspended ceilings (and other nonstructural components) is computed by the codes so-called F_P equation. In lieu of using the code's analytical equation and prescriptive installation, the code [1] writes…*testing shall be deemed as an acceptable method to determine the seismic capacity of components and their supports and attachments. Seismic qualification by testing based upon a nationally recognized testing standard procedure, such as ICC-ES AC 156, acceptable to the authority having jurisdiction shall be deemed to satisfy the design and evaluation requirements* …

At the perimeter, the US building code prescribes the following: a) two adjacent sides are considered fixed. For these sides, a 50-mm wall molding (angle) perimeter wires, and mechanical attachment (pop rivet or screws) between the grid and wall angle is required, b) the opposite two sides re considered free (floating). For these sides a 50-mm wall angle, perimeter wires, and spacer bars are required. In addition, the grid is cut short 19 mm from the face of wall angle. The requirement to use a 50-mm wide angle at the perimeter presents two difficulties: a) it is not architecturally appealing, and b) given that the building walls are not always 100% plumb, it is difficult to obtain a flush perimeter connection since the angle is relatively stiff. To address this issue, the major manufacturers in the US, have all developed alternate seismic clip installation. The suggested alternate installation comprises 22 to 24 mm wall molding and perimeter seismic clips.

Since the early 2,000's, this code provision and shake table testing approach has been used by all the major manufacturers in the US to evaluate their seismic clips. The tests have been successful. As a result, the manufacturers have applied and received favorable evaluation reports from evaluation service agencies. In the evaluation reports, the use of the perimeter seismic clip has been allowed as an alternate installation. Since the publication of the evaluation reports, the use of the seismic perimeter clips have gained acceptance and the alternate installation have been construction in a significant number of buildings in regions of high seismicity. To streamline the process, the task group in charge of nonstructural components for the new and upcoming edition of the the US code (2016) considered explicitly stating the perimeter seismic clips as one of the code prescribed and acceptable installations. On neither fixed nor free side, there is a requirement for the mechanical (screw) attachment of the seismic clip to the wall molding or the building wall. Figure 3 presents the fixed and free edge perimeter schematics for both the code and alternate installations.

Additional research-based tests on larger frames have recently been completed using a variety of installations including systems with perimeter seismic clips. The results from these tests have been less favorable. In particular, [16] showed that the systems with seismic perimeter clip with no screw attachment between the clip and wall molding had a significantly lower capacity and seismic fragility than the code's prescribed perimeter installation. To address this shortcoming, the proposed language in the next edition of the building code (2016) would now require that the perimeter seismic clips on either the fixed or the free sides be attached to the wall molding with two screws. However, no testing or analysis was completed to assess the efficacy of such requirement.



Fixed side, code installation | Free side, code installation

Fixed side, alternate installation | Free side, alternate installation

Fig. 4 Perimeter installation

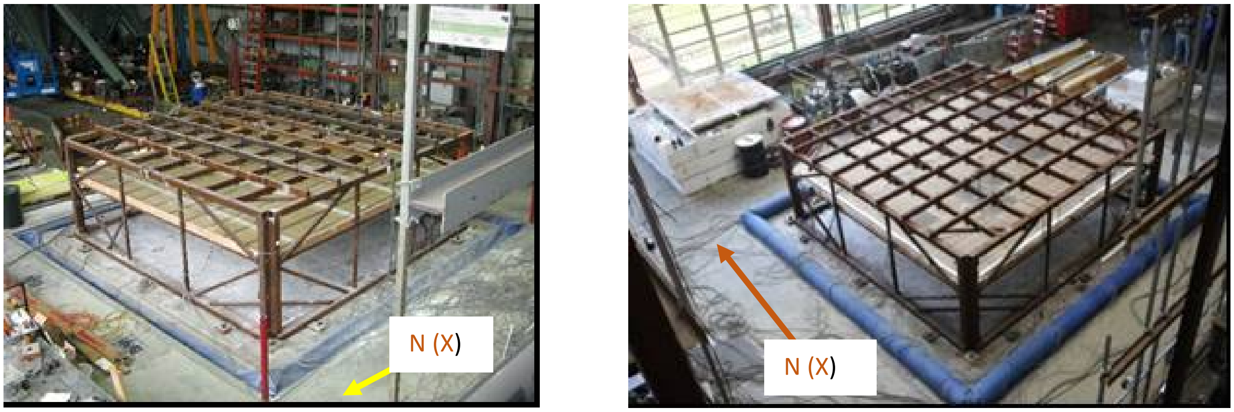
4 Evaluation Program

To examine the seismic performance of the LPSC with alternate installation and DWSC systems in the US, an experimental program comprised of shake table and cyclic testing and finite element analysis were undertaken. In recent years, earthquake simulation testing has been used to assess the seismic performance of LPSC using a comparative method. This approach has significant limitations and in particular, does not provide a minimum testing level that has to be met by a system to be deemed acceptable. The authors ([7] and [8]) have proposed an alternate stand-alone certification procedure.

5 Shake table test program

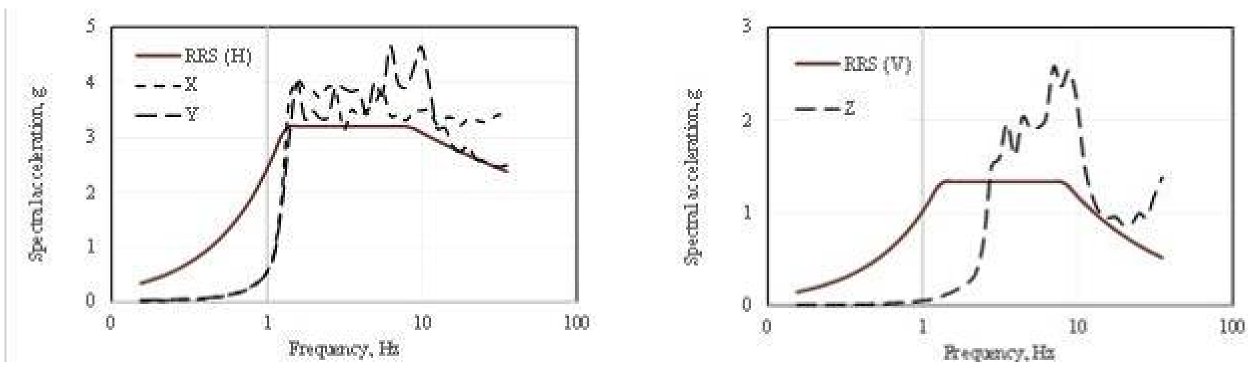
Three test specimens were evaluated: a) DWSC using screw attachment between plaster sheets and grid; b) LPSC installed per code prescriptive requirements, and c) LPSC built using alterative perimeter installation. Fig. 5 presents global view of the DWSC and LPSC used in this evaluation. The instrumentation used to monitor the response of the test specimen comprised accelerometers and displacement transducers and exceeded the minimum requirements of ICC-ES AC156 [9]

The system fundamental frequency was measured at approximately 19 Hz and 10.5 Hz in horizontal (x or y) and vertical (z), directions, respectively. As shown in Fig. 6 presents the target and test spectra for the test with SDS of 2.00 g. As shown in the figure, the test signal enveloped the target spectrum past the filtering limits of the signal.



DWSC LPSC

Fig. 5 Suspended ceiling system used in testing



Horizontal Vertical

Fig. 6 Enveloping of target spectra

5.1 Performance of DWSC

There were no anomalies observed in any of the tests. Therefore, the system was considered certified to S_{DS} of 2.00 g, considered the maximum level in the US for the level of horizontal testing of nonstructural components.

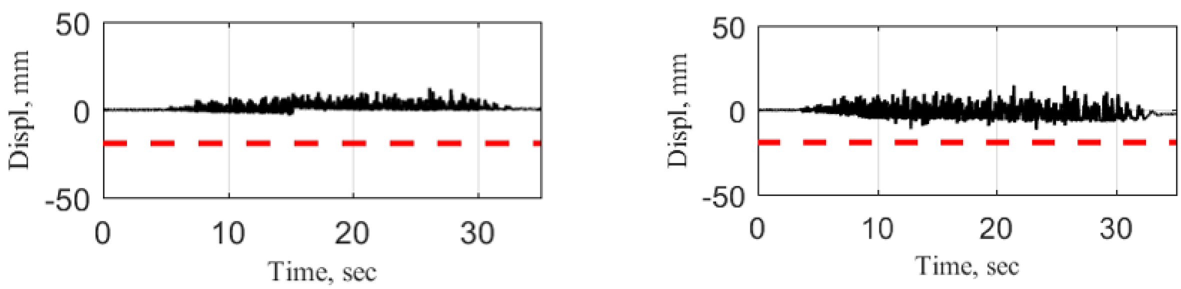
5.2 Performance of LPSC specimens

Table 1 - summarizes the test observations. The specimen with the alternate perimeter installation had equivalent or better performance that the code prescribed perimeter installation.

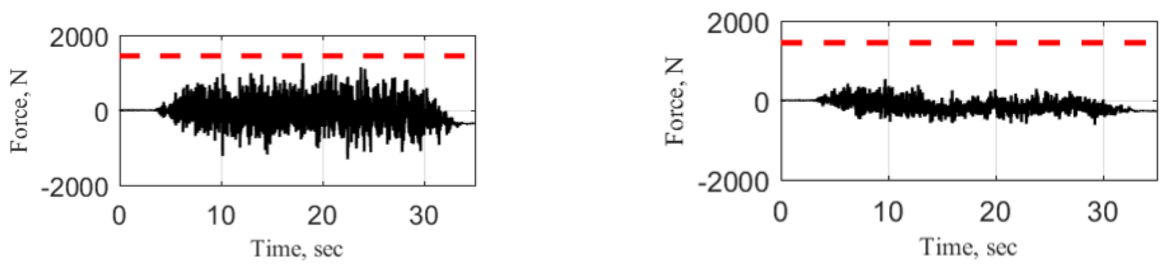
Table 1. Global performance of LPSC specimens

		Seismic clip installation			**Code installation**	
	S_{DS}, g	**1.17**	**1.33**	**1.50**	**1.17**	**1.33**
Anomaly	Panel dislodge	--	--	--	Y	Y
	Panel fall	--	--	--	--	Y
	Perimeter damage	--	--	--	Y	Y
	Grid failure	--		Y	--	Y
Acceptance		Pass	Pass	Fail	Pass	Fail

The tests with S_{DS} of 1.17g—the largest test for which both specimen had acceptable performance—was used for further evaluation. Fig. 7 presents examples of results from the tests. For both specimens, the grid motion is less than the 19 mm gap and thus no pounding against test frame is expected. The code-prescribed installation (SP02) had larger motions that the specimen using the seismic clip. For both specimens the relative motion across the main runner splice was less than 0.8 mm. The computed runner and hanger wire forces (computed as the product of measured strain, elastic modulus, and cross sectional area) for the two specimens were similar and the measured forces were below the main runner splice and hanger wire yield capacities (shown as dashed lines) respectively. Both specimens had acceptable responses



Grid displacement on free side, mm



Grid force, N

Perimter siemic clip installation | Code instalaltion

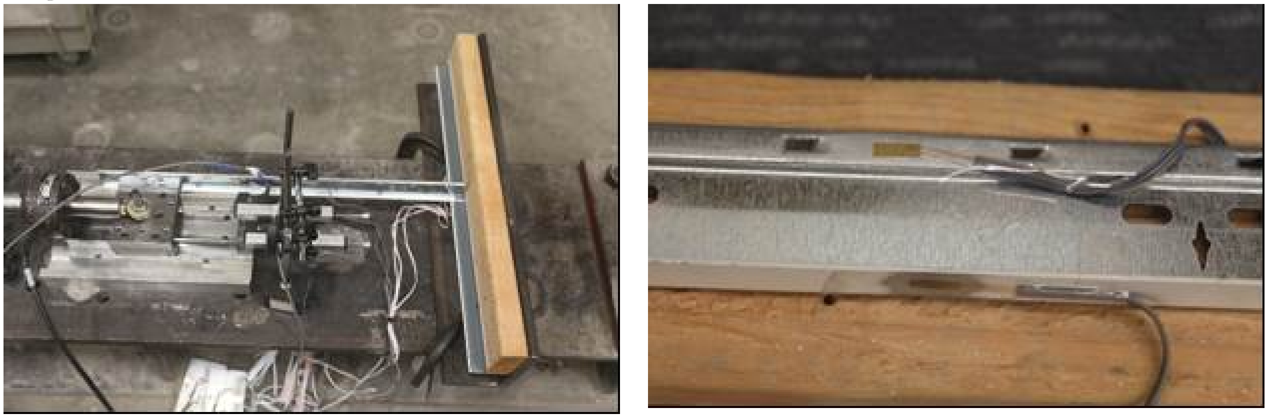
Fig. 7 Specimen responses, S_{DS} =1.17 g,

6 Cyclic tests of LPSC perimeter installations

6.1 Overview

The shake table testing reported in this paper used system inertial weights that were approximately 10% over the code prescribed maximum value of 4.0 psf. However, it is impractical and expensive to test specimens on frames much larger than 5 x 5 m. Therefore component testing have been used in this paper to evaluate both code prescribed and alternate perimeter installation.

For quasi-static testing, an actuator was used to load the web of the grid member (main runner or cross tee) at its center of gravity. The test specimens were subjected to monotonic testing to obtain the backbone curve and cyclic testing to characterize their responses as shown in Fig. 8c, the wall molding was attached to a stiff support using screws. The grid was then attached to the molding at one end. At the opposite end, the actuator supported on a low-friction linear bearing applied loading to the 1-m long member. Instrumentation consisted of a load cell and displacement transducer at the actuator end and strain gages on the wall molding and grid (see Fig. 8d).



a. Test setup b. Instrumentation

Fig. 8 Quasi-static testing

Testing of both main runners and cross tees were conducted and the specimens were tested either monotonically (pull) or quasi-statically (cyclic). For cyclic tests, three specimens were tested to ensure repeatability of results. To assess the performance at the perimeter, a number of perimeter configurations were examined. These included the pop riveted connection and the seismic clip attachment. For the specimens with seismic clips, tests with one or two screws have been completed. All specimens used a 22-mm wide wall angle attached to the support wall with screws. The specimens listed in the table were tested along their longitudinal axis. For the specimens when the ACM7 perimeter clip is used, there was always a screw connecting the grid to the clip, representing the fixed edges of suspended ceilings. Fig. 9 presents drawing of key specimens prior to testing.

Pop riveted connection ACM7 clip with 1 screw ACM7 clip with 2 screws

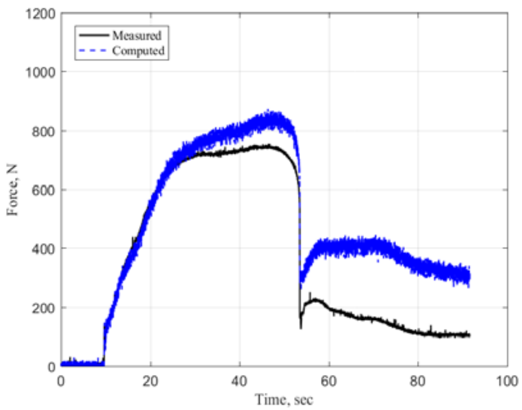
Fig. 9 Specimen perimeter connections

6.2 Monotonic test results

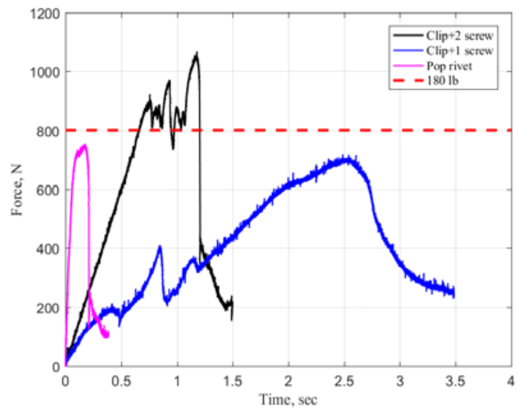
Figure 10 presents key responses for specimens obtained from monotonic testing. These specimens comprised cross tee members that were subjected to monotonic loading along their longitudinal axes.

In Figure 10a, the results for one of the main runners is shown. The measured force corresponds to the directly measured load during experimentation, whereas, the computed force is obtained by multiplying the measured strains, by the Steel's modulus of elasticity and the cross sectional area. As seen in the figure, there is good correlation between the computed and measured forces. Since it is not practical to measure grid forces directly during shake table testing, strain gages can instead be used to compute the distribution of force along the grid members.

Figure 10b presents the force-displacement relation for three specimens with identical setup except for the use of use of pop rivet for SP24, clip with one screw for SP23, and clip with two screws for SP21, all at the perimeter. Also shown in the figure is the dashed line at the 800 N threshold value prescribed in the code for the splice or connection capacity. The specimen with pop riveted connection attained a force of approximately 760 N at small displacement. The specimen with the clip and 1 screw had slightly lower capacity but much larger displacement due to twisting, pullout, and deformation of the clip. The specimen with the clip and 2 screws had axial capacity that was substantially larger than of other specimens and its capacity was above the 800-N limit value.



Applied and computed force responses



Force-deformation response

Fig. 10 Specimen responses, monotonic tests

Fig. 11 presents the test specimens at the conclusions of testing detailing the observed perimeter failure. For the pop rivet specimen the failure was caused by the pull out of the rivet. When clip with a single screw was used, the clip would rotate, deform, and then fail at the screw connection. For the specimen with the clip and 2 screws, the failure mode was the pull out of the screw from the wall angle and the clip remained relatively intact.

Pop riveted connection

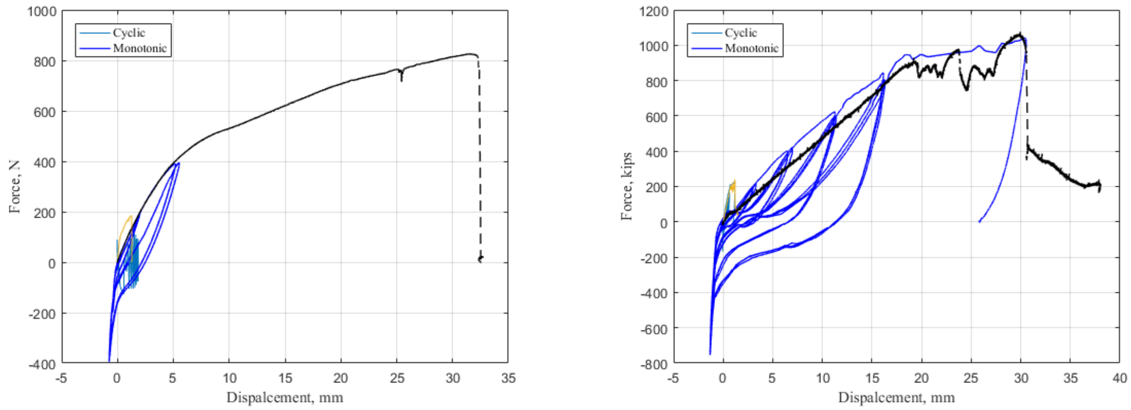
ACM7 clip with 1 screw

ACM7 clip with 2 screws

Fig. 11 Specimens at the conclusion of testing showing failure modes

6.3 Cyclic test results

Fig. 12 presents specimen responses for cyclic tests. Data are shown for specimens with pop rivet connection and for seismic clip with two screws. It is seems that the monotonic curve envelopes and provides a backbone curve for cyclic tests. Furthermore, the specimen with seismic clip and two screws has significantly larger force-deformation hysteresis area than the specimen with pop rivet. Thus, the alternate perimeter installation dissipate more of the seismic energy and thus reduces the demand on the ceiling components.

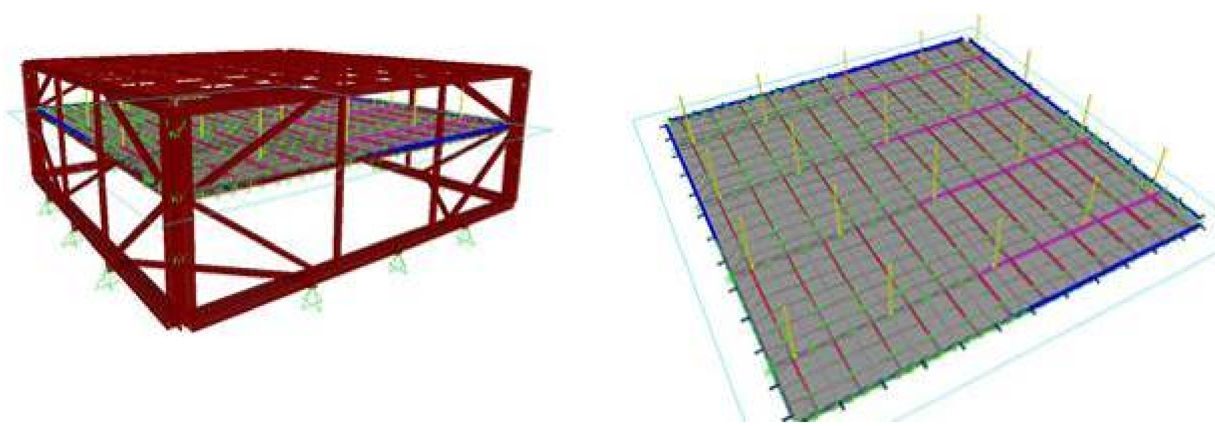


Pop rivet at the peripemeter ACM7 clip with 2 screws at the perimeter

Fig. 12 Specimen force-displacement hysteresis responses, cyclic tests

7 Finite element analysis of DWSC

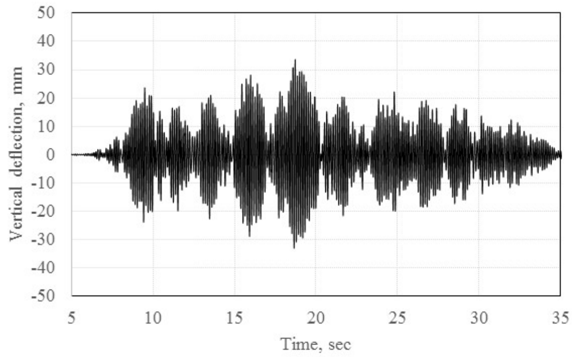
Finite element analysis of the tested DWSC was undertaken. In the model, the support frame was modeled based on the data from laboratory test report [10]. The components of the test specimen were modeled based on the nominal (geometry and material property) manufacturer data [11]. The panels were modeled as two-dimensional shell elements, the grid as frame elements, and the screw attachments between various components as link elements. Fig. 13 presents the finite element model of the test specimen and support frame. For clarity, the components of the DWSC test specimen are shown in the figure.



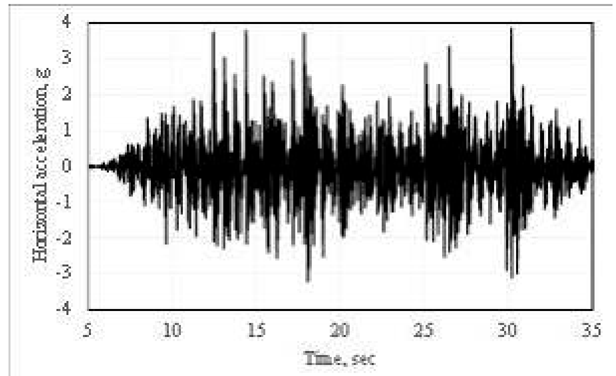
Isoperimetric view DWSC only

Fig. 13 Analytical model

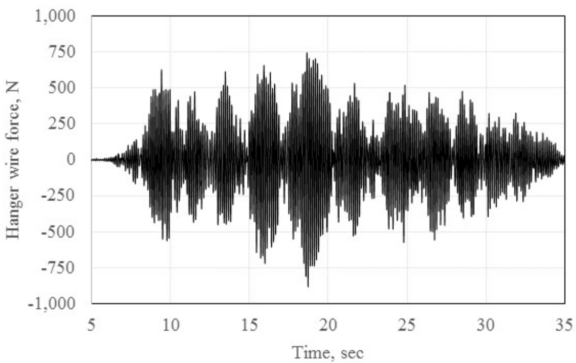
The analytical model was next subjected to seismic loading. The input accelerations for the model were obtained from the shake table accelerations of tests at S_{DS} of 2.0 g. Figure 7 presents examples of the analytically computed results. The maximum vertical deflection at the center of the panel was approximately 30 mm. The maximum measured horizontal acceleration was approximately 4.0 g. The table output horizontal acceleration had peaks at approximately 2.6 g. Therefore, the acceleration response was only amplified by approximately 150%. This low amplification was the result of the rigid attachment of the panels to the grid system. This behavior is likely a key contributor to the good performance of installed DWSC systems in the US during the past earthquakes. The maximum computed hanger wire and attachment screws were approximately 890 N and 70 N, respectively. These values are below the hanger wire pullout and the screw failure loads, respectively, [11].



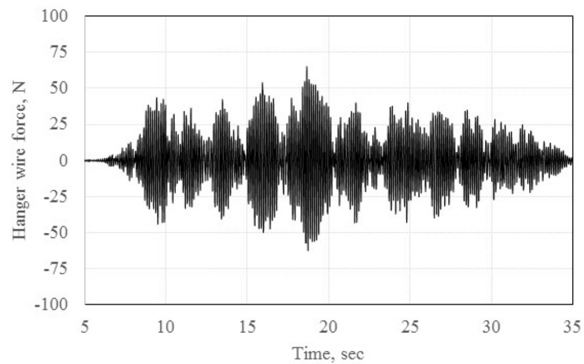
Center deflection



Center horizontal acceleration



Hanger wire force



Force in a typical screw

Fig. 14 Analytical results

8 Conclusions

Based on the discussion presented in this paper the following conclusions are made.

- In the US, DWSC have performed well in past earthquakes. This is reflected in the building code which expects these systems from mandatory requirements
- Shake table testing of the USG DWSC indicated that for systems weighing up to 2.3 psf and sizes up to 5 x 5 m the system can withstand seismic input of up to and including SDS of 2.00 g, the maximum recommended value for shake table testing of suspended ceilings.
- The specimen with the seismic clip, had equivalent or better performance that the code prescribed installation using shake table testing
- The alternate perimeter installation with seismic clip and 2 screws has larger capacity and more energy dissipation than the code prescribed installation.
- When less than 2 screws are used, the performance of the clip connection degrades due to the clip rotation. The new edition of ASCE 7 would require two screw connections on all sides when perimeter clips are used.
- Mathematical model of the test specimen was developed and used to assess key responses.

Acknowledgements

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