SEISMIC PERFORMANCE OF DIRECTLY HUNG SUSPENDED CEILINGS WITH ENGINEERED PERIMETER PRODUCT

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ABSTRACT :

Suspended ceilings have sustained major damage during the past earthquakes in the United States and abroad. This damage has caused injuries, has lead to business interruptions, and has alarmed the building occupants. Industry-sponsored earthquake simulation tests were conducted in the 1980's to investigate this vulnerability. Because of the observed field damage and based on the findings from these tests, the most recent editions of building codes require specific installation measures to mitigate this vulnerability. However, the effect of such measures on the seismic performance of ceilings had not been investigated. Furthermore, the susceptible components, modes of failure, and performance levels had not yet been identified. To investigate these issues, researchers performed seismic qualification and fragility tests to characterize the seismic performance of manufacturer engineering components intended for use at the perimeter.

KEYWORDS: Suspended ceilings, nonstructural component, earthquake damage, seismic qualification, earthquake simulation, perimeter clip

1. INTRODUCTION

Suspended ceilings are a feature of modern commercial and residential buildings (Figure 1) and consist of a grid system, panels, and various attachments as shown. The grid is usually comprised of 0.6 x 1.2 m or 0.6 x 0.6 m modules. In typical installation, either light acoustical or heavier gypsum panels are used. Most installations use lay-in panel. Various attachments—for example light fixtures, air diffusers, and sprinklers—are placed in some modules.

Suspended ceilings have been vulnerable to damage from earthquake, sustaining panel loss and grid failure in moderate earthquakes, even in absence of major structural damage. Such damage has resulted in business interruptions, block of egress during evacuation, and could present life-safety hazard. Consequently, requirements for installation in seismically active zones have been incorporated in building codes. Suspended ceilings are difficult to model analytically. Instead, laboratory testing of full-scale models can be performed to assess the seismic response of these units and to evaluate the current installations spelled out in the codes.

2. SUSPENDED CEILING COMPONENTS AND INSTALLATION

Main runners spanning in one-direction and cross runners framing to these runners orthogonally are used to divide the ceiling area into square or regular modules (Figure 2). The ceiling is suspended from the main structure using vertical hanging wires of at least No. 12 gauge, placed at 1.2 m 4 spacing along each main runner. Mechanical connections are used to splice main runners and attach the main and cross runners. The grid members are typically light-gauge hot-dip galvanized tee sections. Heavy-duty grid members are required in seismic zones. A minimum capacity of 800 N for the grid members and connections, and 450 N for wires is required.

Building codes (IBC 2006 and ASCE 2005) require that ceilings situated in seismic design categories (SDC) D through F, must meet specific perimeter and lateral requirements. A system of wall angles, perimeter wires, and restraints are required along all four edges. The wall angles must be 50 mm or wider. The ceiling must be attached on two adjacent faces to the wall using mechanical connections. On the opposite faces of the grid, a 19-mm wide gap is provided to allow free movement of grid. The perimeter end of the member is supported within 200 mm from the face of the wall with No 12 gauge wires, which should not deviate, by more than 10 degrees from vertical. Spacer bars or other means are provided at the two free edges of the ceiling to provide restraint against lateral spreading of the grid members. When the ceiling area exceeds 93 m^2 lateral restraints are required. The lateral bracing is comprised of a system of splay wires and compression posts. The lateral restraint has a spacing of 3.6 m in each direction; with the first set occurring within 1.8 m of the face of the wall. Four wires, with a capacity of the greater of 900 N or twice the design load, are splayed at 90° from each other and placed at less than 45° from horizontal. Wires are attached to the main runner within 50 mm of an intersection with cross members. A compression strut resists the vertical component of the force induced by splay wires. It is attached between the main runners and the supporting structure.

Figure 1. Suspended ceiling in an office building

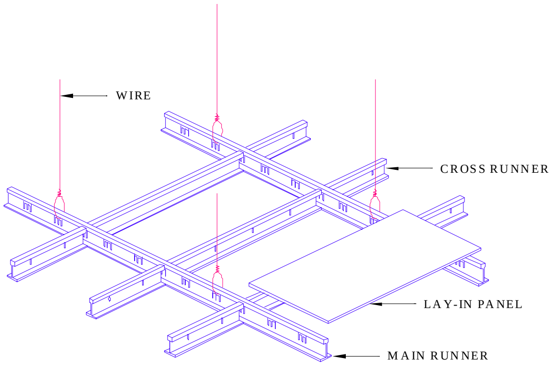


Figure 2. Grid system and lay-in panels

3. PAST SEISMIC PERFORMANCE

Suspended ceilings have been vulnerable to damage from earthquake, sustaining failure in moderate earthquakes, even in absence of major structural damage resulting in business interruptions, block of egress during evacuation, and presenting life-safety hazard. Figure 3 and Figure 4 shows photographs of damaged ceiling during the 2007 Niigata (Japan) and 2008 Sichuan (China) earthquakes, respectively.

Figure 3. Ceiling damage Niigata (Japan) 2007

Figure 4. Ceiling damage Sichuan (China) 2007

4. CODE PROVISIONS

Due to extensive earthquake damage, installation requirements for ceilings in seismically active zones have been incorporated in building codes. The current US Building Code (IBC 2006) and its foundation document, ASCE 7 (ASCE 2005), address the seismic design and acceptance requirements for suspended ceilings.

The code allows for design and evaluation based on either an analytical or an experimental method. The seismic force acting on the component (*Fp*) is calculated from Equation 1.

$$F_p = [0.4\frac{a_p I_p}{R_p}(1+2\frac{z}{h})]W_p S_{DS} \le (1.6 I_p) W_p S_{DS} \qquad (1)$$

In this equation, W , denotes the weight, and I_p, a_p, R_p designate the, importance, amplification, and modification factors, respectively. The location of the component along the building height is indicated by z/h. S_{DS} is the design level spectral acceleration, equal to $2/3F_aS_s$ where S_s and F_a are measures of the short-period spectral acceleration and site condition, respectively, and obtained from ASCE 7. For suspended ceilings, W_p is specified as 190 Pa, a_p equals 1.0, and R_p is 2.5.

The code allows for testing to be performed determining the seismic capacity of ceilings. The test program must meet the requirements of ICC-ES AC 156 (ICC 2007) or other nationally recognized standards. The seismic testing consists of a resonant frequency test, to determine the fundamental frequencies of the test unit; and seismic simulation tests, to assess the seismic performance of the test unit. The seismic force of Equation 1 is used to develop the required response spectrum (RRS). Elements with a frequency exceeding 16.7 Hz are considered rigid and for these a_p equals 1.0. Components with a frequency of less than 16.7 Hz are considered flexible with a_p of 2.5. The earthquake simulator signals should be non-stationary, broadband, and random with energy content from 1.3 to 33.3 Hz. The input accelerations are multi-frequency. The test response spectrums (TRS) should envelope the RRS in the 1.3 to 33.3 Hz range. TRS should also be within 90 to 130 percent of RRS in the amplified region of spectrum.

Seismic qualification is a pass-fail test. The ceiling is tested and if it meets all the structural, operational, and post-test assessment requirements at level of seismic input S_i but not at S_{i+1}, then the ceiling is seismically qualified for use for sites where it would experience seismic loading of up to and including level S_i. Comparative seismic qualification refers to conducting laboratory testing on two similar specimens using different installations, one assembled per code, and the other using an engineered alternative. It is presupposed that if the alternate installation performs as well or better than the code recommended practice during earthquake simulator testing, then this alternate can be used in seismic regions in lieu of the code installation.

Seismic fragility tests are conducted at incrementally increasing input intensity. The objective of the tests is to associate the observed damage with the level of seismic input. Fragility curves show the probability that a limit state would be exceeded as a function of input intensity. Since suspended ceilings are classified as acceleration-sensitive units, the peak spectral acceleration provides an excellent index to measure performance. For suspended ceilings, the fragility curve has a lognormal distribution representing the probability of exceeding a damage state as a function of spectral acceleration.

5. TEST SPECIMENS

To prevent failures similar to the ones observed in past events, IBC 2006 has three requirements for the perimeter: 50-mm wall angles, hanging wires, and spacer bars to prevent spreading of grid members. In the alternate perimeter installation, the wall angel size is reduced to 24 mm, clips are used at all four edges, and spacer bars are eliminated. The alternate perimeter installation (ICC 2007) is intended to improve the aesthetics of the ceiling by reducing the width of the wall angles and to reduce installation cost by eliminating spacer bars. Two sets of tests were conducted using standard and alternate perimeter installations. Figure 5 presents the detail for the standard installation, whereas, the alternate installation is shown in Figure 6.

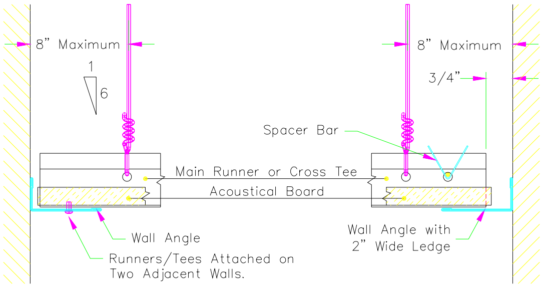


Figure 5. Specimen I: code installation

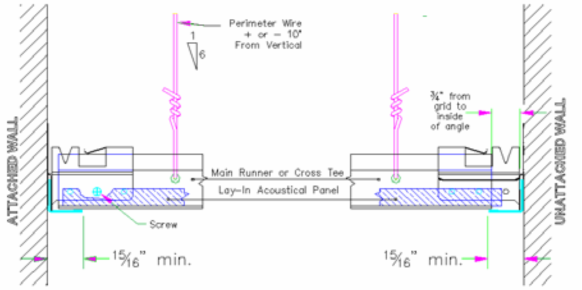


Figure 6. Specimen II: alternate installation

For the two tests, the main runners were spaced 1.2 m on center. Cross-tees were installed 0.6 m on center perpendicular to the main runners forming the 1.2 x 0.6 m modules. The wall angle was fastened to the perimeter walls using screws spaced 0.6 m on center. Main runners were supported 1.2 m on center by 12 gauge steel vertical hanger wires. The North and West side of the ceilings were fixed to the wall angles. On the opposing walls, the grid was not fixed to the wall angles. The lateral bracing consisted of a 20-gauge metal stud used as the compression post and four 12-gauge steel splay wires. The bottom of the post (strut) was screw attached to the main runner using framing screws. The top of the post was attached to the test frame with two No. 10 self-drilling screws. Splay wires were attached to the main runner within 50 mm of the compression post through circular holes in the web of the runner. Splay wires were secured to both the main runner and test frame using a minimum of three tight wraps within 75 mm. The ceiling has an area of approximately 24 m^2. The total unit weight of test specimen was approximately 48 Pa. Figures 7 and 8 depict specimens I and II prior to start of tests.

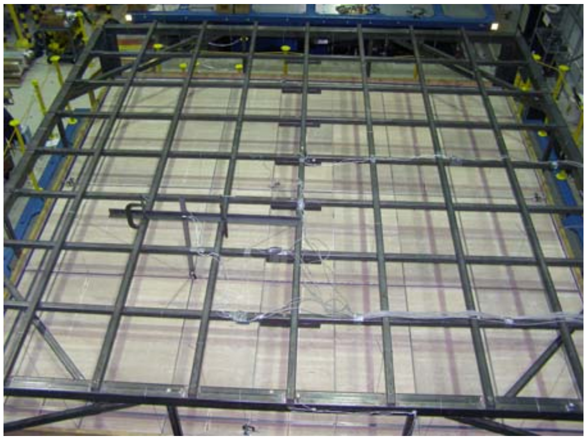


Figure 7. Specimen I prior to testing

Figure 8. Specimen II at start of testing

6. SEISMIC TESTING PROGRAM

One of the two six degrees-of-freedom earthquake simulators at the University at Buffalo's Structural Engineering and Earthquake Simulation Laboratory was used for laboratory testing. The earthquake simulator is capable of producing peak horizontal spectral motions of up to 3.0g. Acceleration histories were synthesized such that their response spectrum (TRS) closely matched the AC-156 RRS. A 4.9 x 4.9 m test frame constructed of HSS sections was used to test the suspended ceilings. The frame was designed so that its properties would represent a typical story in a multistory building. The frame was attached to the simulator platform using high-strength bolts. The frame was intended to be sufficiently stiff so as not to amplify the simulator accelerations. It had fundamental frequencies of 17.5 Hz in horizontal and 9.5 Hz in vertical directions, respectively. Once the ceiling is installed, the system frequency was at the plateau of RRS curve.

Triaxial resonance search tests to establish the fundamental frequency of the system; and random multi-frequency seismic simulation tests comprised the test program. The seismic tests were conducted starting at a peak spectral acceleration of 0.25g, and incremented at 0.25g intervals up to 3.00g (the limit of the simulator signal). Conservatively, all evaluations were based on the measured accelerations at top of the simulator extension platform. Larger accelerations were obtained at the center of the test frame roof. Accelerometers and displacement transducers were used to monitor the response of the simulator platform, the test frame, and the ceiling grid. Triaxial accelerometers were placed at the center of platform, test frame, and grid. Displacement transducers also monitored motion at the perimeter.

Two limit states (or modes of failure) were defined for the seismic qualification tests. These limit states were as following:

- Loss of lay-in panels: The loss of an individual panel does not constitute failure in typical application. What is of interest is the cumulative loss of panels as a percentage area of the ceiling system. Once panels fell in one test, they were not replaced in subsequent tests.
- Grid failure, denotes buckling, dislodging, or collapse of grid members either at the perimeter, at splices, or at connections.

7. EXPERIMENTAL RESULTS

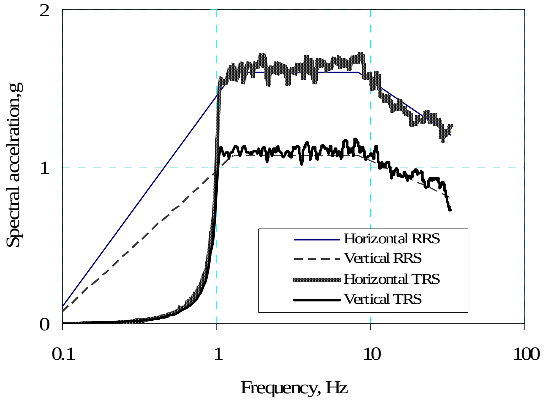
Table 1 summarizes the peak recorded acceleration and the 5%-damped peak spectral intensity for the seismic qualification tests. For example at the nominal 2.00g test, the spectral horizontal and vertical acceleration ordinates are 7.3g and 9.4g. Similar values were obtained for Specimen II.

Table 1. Perimeter installation for the two specimens

	Specimen I								Specimen II							
Direction	Horizontal				Vertical				Horizontal				Vertical			
Location	Simulator platform		Top of frame		Simulator platform		Top of frame		Simulator platform		Top of frame		Simulator platform		Top of frame	
Accel (g)	A_{max}	Sa	A_{max}	Sa	A_{max}	Sa	A_{max}	Sa	A_{max}	Sa	A_{max}	Sa	A_{max}	Sa	A_{max}	Sa
1.5	0.8	1.9	1.6	6.3	0.6	1.3	2.4	7.0	0.8	1.8	1.6	5.6	0.6	1.3	2.2	7.5
1.75	0.9	2.2	1.9	6.6	0.7	1.6	3.0	10.9	0.9	2.1	1.9	6.5	0.7	1.8	2.4	10.3
2	1.3	2.5	2.0	7.4	0.9	1.7	3.8	9.7	1.2	2.4	1.9	7.5	0.7	1.6	3.0	9.8
2.25	1.5	2.5	2.2	8.6	0.8	1.9	3.4	12.8	1.4	2.7	2.0	8.0	0.8	1.8	2.9	12.6
2.5	1.6	3.1	2.7	9.5	0.9	2.0	4.0	16.4	1.6	3.0	2.2	8.8	0.9	2.0	3.3	13.5
2.75	1.8	3.4	2.7	8.6	1.0	2.3	4.8	20.7	1.7	3.2	4.4	9.4	0.9	2.2	3.9	15.0
3	1.9	3.8	2.8	9.9	1.1	2.5	4.5	24.6	1.8	3.5	2.7	10.5	1.0	2.4	4.7	18.0

Figure 9 shows the TRS at the nominal 1.50g test. The TRS matches and exceeds the RRS for this and all other tests. Specimen I was *seismically qualified* to 1.50g, on this frame, since it passed this test and reached a limit state in the subsequent test when the first panel fell. Specimen II did reach its limit state of panel loss at 2.00g test, and thus was qualified to 1.75g.

Figure 10 presents the percentage area of fallen panels as a function of the nominal spectral acceleration intensity. Data for both specimens are presented. Lognormal curves can be fitted to the test data. Note that the specimens have similar curves. For example, it is anticipated that the 50%-area loss threshold will be reached for both specimen at a spectral acceleration of approximately 3.75g. Neither specimen experienced grid failure.



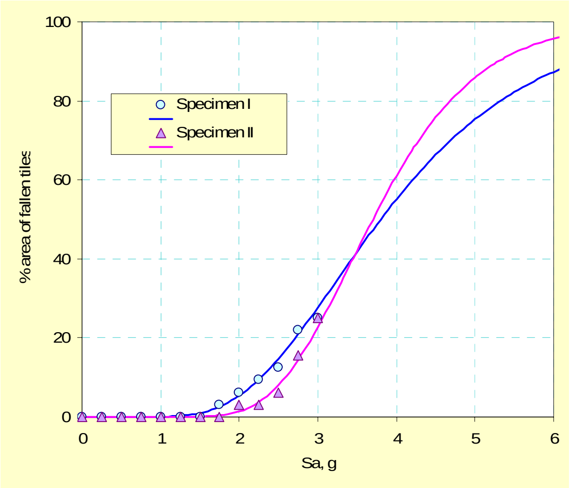


Figure 9. RRS and TRS curves, 1.50g test

Figure 10. Log-normal fragility fitted curves

Figure 11 shows the measured acceleration along one of the unsupported edges for both specimens. Individual tests are separated by the dashed lines. The alternate installation has similar or smaller accelerations for all the recorded tests.

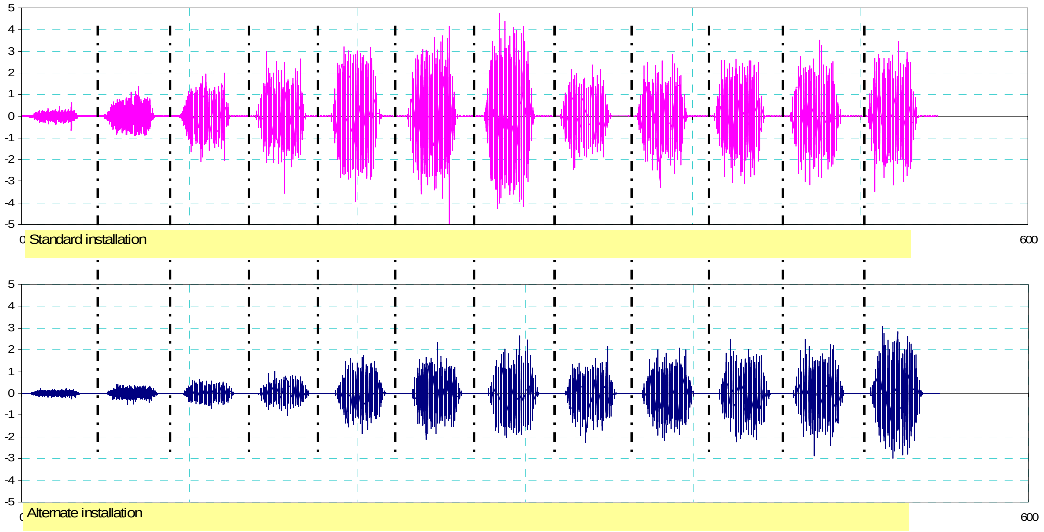


Figure 11. Recorded acceleration on an unsupported edge

To assess the performance of the specimens, critical responses at the edges of the ceilings were evaluated. Figure 12 presents the measured acceleration maxima along the supported edge (west side) of the ceiling specimens. Note that the ceilings have similar responses. Figure 13 depicts the recorded displacement maxima along an unsupported (south side) of the ceilings. The displacements are smaller for Specimen II that uses the alternate perimeter components.

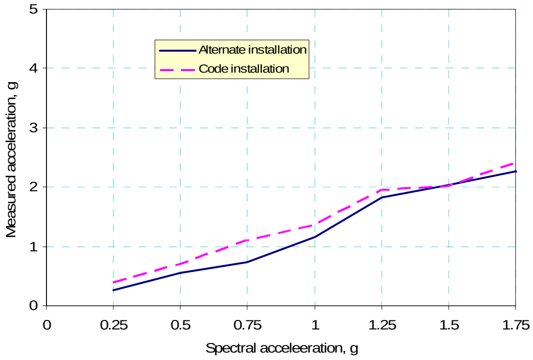


Figure 12. Measured acceleration along supported edge

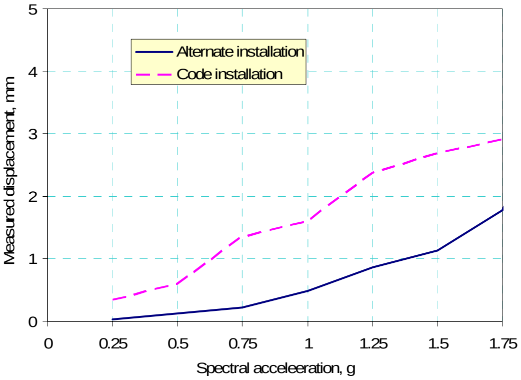


Figure 13. Measured displacements along unsupported edge

The photographs of Specimen I and Specimen II at the conclusion of tests are presented in Figure 14 and Figure 15, respectively. Note that both systems have lost eight panels. However, the patterns of lost tiles differ slightly for the two systems.

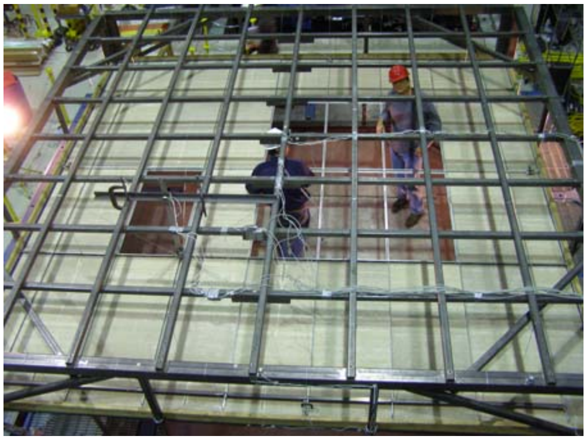


Figure 14. Specimen I at conclusion of testing

Figure 15. Specimen II at test completion

Since Specimen II performed as well or better as Specimen I, had similar or smaller responses, and it reached its limit state at a higher spectral acceleration, then the alternate installation used for Specimen II is considered seismically *qualified by comparison*, on this test frame, for use at regions of high seismicity.

8. SUMMARY AND CONCLUSIONS

Nonstructural components comprise a large portion of building inventory. In the past earthquakes, suspended ceilings have sustained damage in moderate events and in well-designed buildings, resulting in loss of operation and expensive repair costs. To mitigate such damage building codes have developed strict installation procedures. An alternate perimeter installation clip was engineered and tested on earthquake simulators. From the tests reported herein, the following conclusions are drawn.

- Laboratory tests can be used for seismic qualification of suspended ceilings
- Comparison qualification is proposed as means of evaluating the seismic performance of alternate installation components
- Ceilings using alternate installation components performed as well or better than the code installation.

When perimeter clips were substituted for spacer bars and wall angles were reduced in size, there was no noticeable change in response.

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