Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 147

CURRENT CODE REQUIREMENTS AND QUALIFICATION TEST STANDARD DEVELOPMENT FOR SUSPENDED CEILINGS

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ABSTRACT

To mitigate the extensive damage of the suspended ceilings seen in the past earthquakes, the building codes have developed prescriptive construction and installation requirements. The code requirements have evolved through the successive code cycles and attempt to incorporate field observations and experimental findings. Alternatively, ASCE/SEI 7-05 allows seismic qualification of nonstructural components by shake table testing. Such approach has been used extensively by the major manufacturers in recent years in the United States for the purpose of qualification of their products. However, to date, no component-specific test standard has been developed for the suspended ceilings. As such, in many cases, it has not been clear to the manufacturers what qualification and evaluation procedures to follow. It is proposed to develop a test standard that addresses the unique features of these non-structural components.

Introduction

Directly hung suspended ceilings—comprised of light galvanized grid elements, acoustical or gypsum panels, and attachments placed in grid modules—are a common feature of commercial and residential buildings. Suspended ceilings have been damaged in earthquakes, with damage ranging from loss of panels (see Figure 1) to grid collapse (Figure 2). Such damage has resulted in business interruptions, block of egress during evacuation, and could present life-safety hazards.

Figure 1. Fallen panels, North Chino Hills (M 5.4, 2008).

Figure 2. Partially collapsed ceiling, Sichuan Earthquake (M8.0, 2008).

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To address the seismic vulnerability of suspended ceilings, specific installation procedures have been prescribed in the code. Additionally, seismic qualification by either analytical or experimental procedures is allowed in the code.

History of Building Seismic Code Provisions for Suspended Ceilings (NEHRP 1994 to ASCE 2010)

Seismic requirements for suspended ceiling systems provided in building codes in the United States have evolved significantly since the early 1990's. In the early 1990's there were 3 model building codes in the United States. These codes were very regional in their focus with the *Standard Building Code* (SBCCI 1991) focusing on wind issues, the *National Building Code* (BOCA 1996) focusing on ice and snow and the *Uniform Building Code (UBC)* (ICBO 1997) focusing on earthquake loads. State and local jurisdictions adopted these codes by ordinance and in some cases provided amendments to the document. Between the 1950's and 1990's, seismic requirement in the United States were generally based on those found in the UBC. Since the early 1980's, the UBC contained a standard for the design standard and installation (Standard 25-2) of suspended ceiling that had similar seismic requirements to those contained in CISCA Zone 3-4 requirements (CISCA 2004). The UBC also contained lateral seismic coefficients and minimum seismic weight requirements to be used in the design of suspended ceilings.

The primary seismic criteria for suspending ceiling systems found in ASCE/SEI 7-10 was actually developed in the 1991–1994 period and incorporated in 1994 NEHRP Recommended Provisions (which were actually published in mid-1995). The changes developed in the 1994 NEHRP Recommended Provisions were greatly influenced by the seismic performance of suspended ceilings in the 1989 Loma Prieta and 1994 Northridge Earthquake. The 1994 NEHRP Recommended Provisions for ceilings were developed by Technical Subcommittee 8 (TS-8) of the PUC which had responsibility for developing provisions for architectural, mechanical and electrical components, equipment and systems. It was agreed to by TS-8 that the suspended ceilings should be designed based upon the CISCA guidelines that were developed in the 1980's for use with the UBC. Because the NEHRP Recommended Provisions did not use the UBC seismic zones and used different equivalent static forces for design, the CISCA guidelines needed to be adopted with some modification, which made them, comply with and are consistent with the NEHRP Recommended Provisions.

Significant additional technical requirements developed by TS-8 were also added into the 1994 NEHRP Recommended Provisions for suspended ceilings installed in buildings, which are assigned to the highest seismic design categories based on a combination of both severity of design ground motions and building occupancy. The primary changes which were required in buildings assigned to the highest seismic design category:

- It was observed that ceiling damage in earthquake initiated with ceiling tiles falling out at the perimeter of large rooms and at columns. It was felt if the seat angle width were increased; the ceiling tiles would not fall out and ceilings could survive design level motions without collapse. Because of this in rooms with an area of 1000 square feet, seat widths of closure angles were increase to a minimum of 2 inches from the more typical

7/8 inch. The 2 inch dimension was based on simple pendulum analyses of suspended and design ground motions.

- It was also observed that serious water damage resulted because of the interaction of sprinkler drops with ceiling systems through which they penetrated. To limit this damage to sprinkler drops a 2 inch oversize penetration hole was required around sprinkler drops which in turn required and oversized covering plate around the drops. The purpose of the hole was to accommodate the relative movement between the ceiling grid and sprinkler drop. The oversized hole was based on the same simple pendulum calculations as the increased seat angle width. It should be noted that if an articulating sprinkler drop was provided that could accommodate the relative displacement, the requirement for the oversize penetration hole could be waived.
- Heavy duty ceiling grids were required which were believed to improved the survivability of the ceilings..

The TS-8 recommended provisions were incorporated into the 1994 NEHRP Recommended Provisions and into subsequent editions of the NEHRP Provisions, the IBC and ASCE/SEI 7 without change until the 2010 Edition of ASCE/SEI 7. The ceiling industry developed an ANSI standard ASTM E-580 which incorporated the requirements of the CISCA guidelines into mandatory language as well as most of the special additional requirements of ASCE/SEI 7 (which were based on earlier versions of the NEHRP Recommended Provisions). This allowed ASCE/SEI 7 to remove the CISCA requirements and most of the special additional requirements that were added in ASCE/SEI 7.

One other significant change that affected the design of ceiling systems occurred in the 2005 edition of ASCE/SEI 7-05. A section was added that permitted two alternate means of satisfying the seismic requirements for nonstructural components including suspended ceiling system. The two alternate methods were shake table testing and experience data and a shake table qualification specification, AC-156, was specially identified as being an acceptable procedure. Some ceiling manufacturers have became aware of the additional special requirements of the IBC and ASCE/SEI 7, have decided to test develop new ceiling designs that satisfy the alternate seismic qualification requirements of ASCE/SEI 7 while at the same time not requiring the some or all of the special requirements of ASCE/SEI 7. It is interesting to note that the ceiling manufacturers have reported that based on the shake table tests that they had performed the assumptions used to develop the special requirements of ASCE/SEI 7 for standard ceiling were fairly well confirmed by the testing. It should also be noted that the ceiling manufacturers are now in the process of developing their own shake table testing standards adapted from AC-156 that will apply specifically to the testing of ceilings. It is anticipated that the resulted standard will be referenced in the version of ASTM E-580 and the next addition of ASCE/SEI 7.

Recent Experimental Investigations

Overview

In recent years, the three major manufacturers of suspended ceiling grids in the United States have conducted earthquake simulator testing of their products at the University at Buffalo

(UB) and at the University of California at Berkeley (UCB), and have utilized an elevated frame with a footprint of 16 x 16 ft. Figure 3 shows the elevation of test frame used at the UB (Gilani, Reinhorn et al. 2008). The test frame at UCB is depicted in Figure 4 (Takhirov 2009).


Figure 3. UB Test frame.


Figure 4. UCB test frame.

Although adequate for initial studies, the frame and the procedure used for testing might not be ideal for seismic qualification studies. Close examination of experimental data have shown that revisions to the current practice is warranted. Several key issues are identified here.

Applicability of AC-156 as the Test Standard for Suspended Ceilings

The current test procedure aims to follow requirements of the AC-156 (ICC-ES 2007). The application of AC-156 for seismic testing of suspended ceilings may be questionable for three reasons.

- AC-156 was originally developed (Gatscher et al. 2003) for seismic evaluation testing of equipment that have a *limited number of attachment points to a structure*, e.g. electrical cabinets, chillers, medical equipment and so forth. In contrast, suspended ceilings are large systems, are distributed in space with many attachment points between the ceiling and the wall of the structure. The size of one partition of a ceiling system can be as large as 2,500 ft^2.
- Suspended ceiling systems are tested in a test frame attached to a shaking table. Hence, the *accelerations at the attachment points are much higher than that at the table level*, due to the amplification produced at the frame resonant frequencies resulting in over testing at frequencies closer to frame resonance. Such situations could alter the limit states and failure modes of suspended ceilings in comparison to those that are field installed.
- AC-156 requires the measurement of anchoring loads at each attachment point. Such measurements are impractical for suspended ceilings given the large number of attachment points and the complexity of the attachment methods.

Response Amplification by the Test Frames

Suspended ceiling systems are currently tested in the steel frame attached to the earthquake simulators, either at the University at Buffalo (Gulec and Whittaker 2007), or at the PEER center (Takhirov 2009). The frequencies of the frame with and without the ceiling system are presented in Table 1. The ceiling weight alters the vertical frequency significantly.

Table 1. Resonant test frame frequencies (Hz) with and without suspended ceiling.

Location →	**West**			**Center**			**North**		
Configuration	X	Y	Z	X	Y	Z	X	Y	Z
Frame alone	NA	NA	NA	21.4	20.1	13.6	NA	NA	NA
Suspended ceiling installed	21.6	21.7	21.6	21.6	21.7	9.4	21.6	21.5	21.6

In the current practice, the shaking table motion's test response spectra (TRS) envelopes the AC-156 required response spectra (RRS). The TRS is measured accelerations is at the table level. The accelerations at the ceiling attachment points on the frame are larger. A typical plot of the spectra at different elevations of the frame during the sine sweep test is presented in Figure 5. As shown in the figure, the TRS at the table closely envelopes RRS. However, the response spectra at the attachment points of the ceiling system are significantly amplified because of the flexibility of the frame.

Similar amplification was observed during seismic tests; see Figure 6. The flexibility of the frame fails to follow the main idea behind the AC-156 development which is to test non-structural components rigidly attached to the shaking table. In this methodology, amplified motions, intended to account for the building's dynamic properties and flexibility, are used as the input to the shake table to account for the flexibility of the mounting frame.

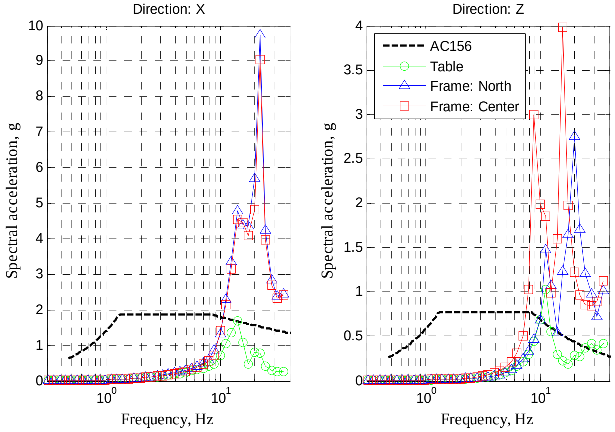

Figure 5. Amplification of response spectra due to frame properties (sine-sweep tests).

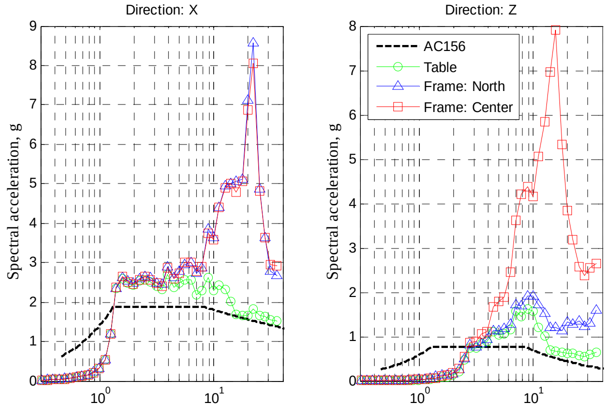

Figure 6. Amplification of response spectra due to frame properties ($S_s = 1.75$).

The Cycle Counts in Grid Displacement Response

The ASTM cycle counting procedure (ASTM 1997 and Downing et al. 1982) is used to count number of cycles in the relative displacement record. The position transducer was recording displacement of the grid relative to the south wall in the X direction. The plot for $S_s=1.75$ is shown in Figure 7, whereas Figure 8 shows the cycle count for $S_s=2.30$. Both plots show that the grid experiences large number of small amplitude cycles and small number of large amplitude cycles. In the practice of component testing of the suspended ceiling systems a detailed study on cycle counts is necessary to develop an appropriate test loading protocol.

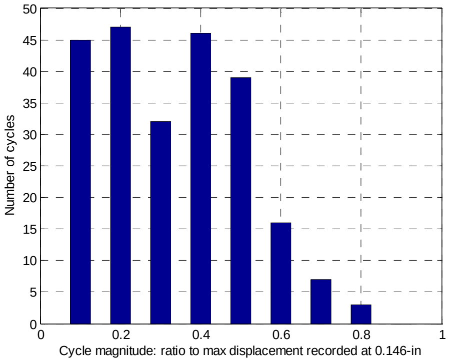

Figure 7. Cycle counts at $S_s=1.75$.

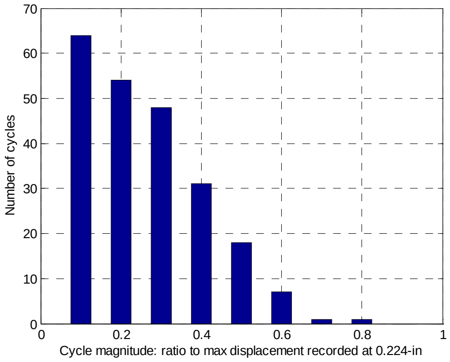

Figure 8. Cycle counts at $S_s=2.30$.

Force Estimate in Grid Members

Data obtained from the sine sweep test was used to estimate the force versus displacement relationship for the cross tee on which the position transducer was installed. Since no strain gages were installed on the grid and load in the tee was not directly measured during the test, the inertia force imposed on the tee was estimated from the difference between the frame wall (floating side) and grid recorded accelerations. The portion of the grid displacement response with regular cycles at 13.5 Hz (resonance frequency of grid) was selected for analysis. The displacement versus relative acceleration curves for a single cycle and several cycles at this frequency are shown in Figure 9. The curves show that the cycles are regular repeatable. Similar displacement-acceleration plots were extracted from the triaxial seismic tests. Two sets of results are derived from two different tests with $S_s=1.75$ and $S_s=2.30$ and are presented in Figure 10. The acceleration exceeds 3.0g for $S_s=1.75$ test and 4.0g for $S_s=2.30$ test. For 2.5 psf tiles, the total weight of the suspended ceiling was approximately 800 lbs, resulting in a force of 100 lbs on each of the 8 Tees for 1.0g acceleration. In the S_s=1.75 test, it would be at least 3 times greater (300 lbs), and in S_s=2.30 test it would be at least 4 times larger (400 lbs). Correlation of such estimated forces with the building code prescribed values would be useful.

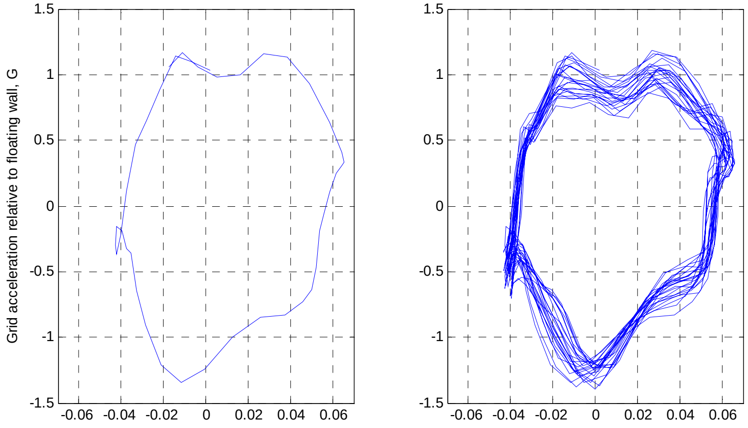

Figure 9. Displacement cycles at 13.5 Hz (sine sweep excitation).

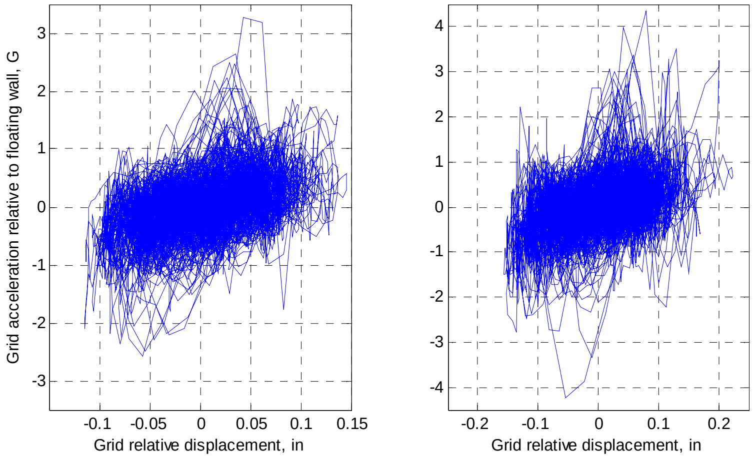

Figure 10. Displacement cycles in seismic tests at $S_s=1.75$ (L) and $S_s=2.30$ (R).

Components of a Test Protocol and Qualification Standard for Suspended Ceilings

Overview

It is envisaged that the qualification test protocol will be developed as a collaborative effort among practitioners, code officials, and academia incorporating the following components. The test method should have the objective of reproducing the observed field performance in the laboratories. Literature survey, analysis, and experimentation will be required to address the issues stated above.

- Design of the mounting frame size and properties. Although not anticipated that the frame will simulate a particular building type, it should conservatively, but realistically envelope the expected performance of various structure types both horizontally and vertically.
- Review of the test spectra provided with AC-156 and determination if the spectra needs to be adjusted for the ceiling tests. Also developing an understanding of what the appropriate horizontal and vertical amplification factors should be for the test frame.
- Requirement for the floor and frame vertical properties. To realistically represent field conditions.
- Procedure for development of input histories. A detailed research program was conducted for seismic qualification of substation equipment. A similar program can be implemented.
- Performance targets and qualification levels. Intended to establish limit states of failure and the corresponding target input intensities.
- Qualification type. A single pass-fail qualification to a level predetermined based on performance levels and the expected ground or spectral intensity at a site. Several qualification levels such as low, moderate, and high can be established. This type of testing will be used in lieu of comparative testing.

- Number of tests. Single qualification levels can be used by manufacturers. Alternatively, incremental testing can be used to assist researchers in developing fragility data.
- Collection of sufficient data to assess qualification. In addition to AC-156 requirements, loading in lateral bracing components, force level at the perimeter, and the grid accelerations should be monitored.
- Correlation of qualification levels with the requirements of the building code. The performance targets and qualification level need to correspond (with a factor of safety) to the code prescribed failure limits and capacity requirements for system components.

Experimental Phase

To address the current deficiencies regarding the test data, a NEES grand challenge has been approved to conduct full scale testing of suspended ceilings and other nonstructural components. This larger test frame is currently under design (Reinhorn 2009). The test results from this project will be used in the future to facilitate the development of a testing standard for suspended ceilings.

Analytical Phase

Various archetypes of buildings will be subjected to a suite of input histories. From analysis, the floor (and roof) response spectra can be developed. This data will next be averaged over the archetypes of selected structures to determine analytically the RRS. Archetypes will be selected to encompass building framing, construction, and number of stories. An example is presented here.

A typical office building was modeled (CSI 2009) for analysis. The structure shown in Figure 11 is a five-story moment frame designed per code requirements. It is comprised of three bays of special moment resisting frames, and two bays of gravity framing on each side of the moment resisting bays. Typical bays are 30 ft wide and stories are 13 ft tall. The fundamental period of the building is approximately 1.6 sec. Three records were spectrum matched to the target design spectrum. Figure 12 depicts the design target spectrum and the input response spectra of the three records

Figure 11. Example building.

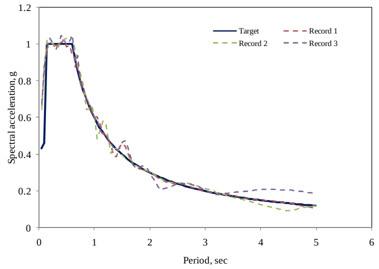

Figure 12. Spectrum matched.

The model was then analyzed and the floor accelerations at various floors were extracted, see Figure 13. Figure 14 shows the distribution of the total floor acceleration along the building height for the three records as dashed lines. Data is normalized with respect to the ground acceleration. Analysis of other archetypes with additional records can be used to develop the envelope of floor spectra that can then be used to determine the RRS and the horizontal amplification factor.

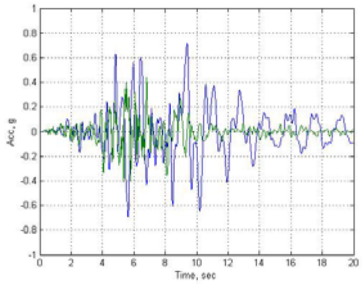

Figure 13. Floor accelerations roof and ground, record 1.

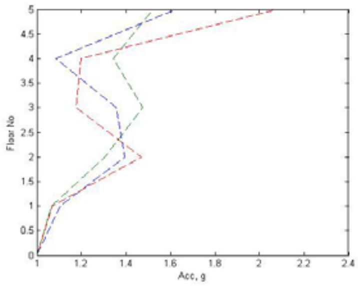

Figure 14. Distribution of maximum floor acceleration along building height.

Conclusions

Based on analysis, the following conclusions are drawn in regards to the current test methodology and the requirements for a future test standard to be developed in the future.

- The design and installation requirements in the building codes have evolved through the code cycles and have attempted to conservatively provide ceilings that have a minimum seismic performance in the earthquakes.
- The current test procedure for seismic evaluation of suspended ceilings has several shortcomings, including:
  - The current test frame and standard fail to replicate the failures observed in the aftermath of past earthquakes.
  - Lack of adequate rigidity in all three directions and all possible earthquake impacts should be accounted in the required response spectra as it is done in the AC-156 document.
  - Inadequate floor plan resulted in high frequency vibrations in the ceiling system,
- A new test standard should be developed incorporating the following:
  - Performance states and qualification levels
  - Enhanced data collection including grid displacement monitoring and direct measurements of the loads in the grid and wires
  - More specific requirements on time history generation
  - Suspended ceiling-specific required response spectra for distributed systems

Acknowledgements

The experimental data used in this report was supplied by Mr. Lee Tedesco of USG Interior Inc., and Mr. Tony Ingratta of Chicago Metallic Corp.

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