Seismic Fragility of Suspended Ceiling Systems

A. A. Echevarria & A. E. Zaghi
University of Connecticut, USA

S. Soroushian & E. M. Maragakis
Center for Civil Engineering Earthquake Research, University of Nevada, Reno, U.S.A.

15 WCEE
LISBOA 2012

SUMMARY:
An analytical model is advanced for study of suspended ceiling systems with acoustic tiles. The model is able to capture several response characteristics of the system including elastic deformations, gap closures between ceiling tiles and tee beams and between tee beams and partitions walls, the out-of-plane vibration of supporting floor decks, and the uplift of ceiling tiles. Two seismic bracing conditions are assumed for models of two ceiling areas. Both models consist of a tee beam grid, acoustic ceiling tiles, and hanger wires. The braced model also includes splay wire bracing and a compression post with oversized perimeter gaps on two boundaries. The models are used to comparatively study the seismic fragility of smaller and larger area ceiling systems in braced and unbraced conditions. Analysis results are presented in the form of fragility curves based on unseating of the grid and dislodgment of ceiling tiles. The probability of damage in unbraced system was found to be higher than that of a braced system due to the unseating of the tee beam grid at the ceiling perimeter. However, the braced system induces tiles to exceed their uplift limit at a lower peak floor acceleration (PFA) than that of the unbraced system.

Keywords: Seismic, Fragility, Nonstructural System, Suspended Ceiling System

1. BACKGROUND

Nonstructural systems represent 75% of the loss exposure of U.S. buildings to earthquakes, and account for over 78% of the total estimated national annualized earthquake loss (Reinhorn et. al., 2010). The failure of nonstructural components can inhibit a building from remaining operational after an earthquake and in some cases may endanger the life safety of its occupants.

Suspended ceiling systems with acoustic tiles are widely used in commercial and residential buildings. Due to the lack of system-level studies, the seismic response of suspended ceiling systems is poorly understood. Current design standards do not explicitly provide any guidelines for the seismic design of such suspended "structures" due to their heterogeneous and complex construction (Reinhorn et. al., 2010). Several ceiling manufacturers have developed basic proprietary seismic resisting details for their products. However, the damage limit states and seismic fragilities of these systems are not yet comprehensively investigated due to the lack of system-level experimental studies and modeling capability. In addition, modern protective technologies, which are readily used in structural systems, have never been applied to these systems. Multiple suspended ceiling models have been experimentally studied at the University at Buffalo (Reinhorn et. al., 2012) to identify the seismic deficiencies and develop the seismic fragility of ceiling systems. However, these types of experimental studies are costly and time consuming. In addition, shake table experiments for very large ceiling areas and nonconventional geometries are not possible due to the physical constraints of the laboratories and shake tables themselves. Currently there is no numerical simulation technique that enables the study of seismic behavior of suspended ceilings.

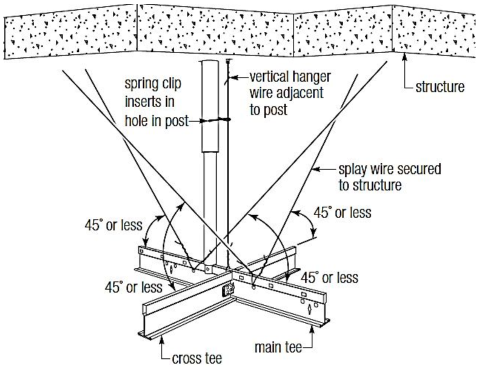
In the course of the project presented in this paper, an analytical model was developed for suspended ceiling systems through the use of SAP2000 structural analysis software (Computers and Structures, Inc, 2011). This modeling technique was utilized to conduct a series of seismic fragility studies for these systems. This project was aimed at understanding the effect of basic physical and mechanical parameters, such as weight of the acoustic tiles on system response, and performing a comparative study between seismically braced and unbraced ceiling systems of two ceiling areas. The smaller and larger ceiling systems selected are $13.4m^2$ and $72.8\ m^2$, respectively. Each ceiling area was investigated in braced and unbraced conditions using a set of twenty-four triaxial time history acceleration excitations. The results of the nonlinear time history analyses are used to develop fragility curves for each of the four cases.

2. SUSPENDED CEILING SYSTEM

Suspended ceiling systems are a nonstructural component installed within commercial buildings to serve as an aesthetic barrier between electrical, mechanical, and piping systems and the living space below (Fig. 1a). The entire ceiling grid is hung from the structural floor above. The area above the suspended ceiling is called the plenum space and can vary from 0.3m to over 3.0m in commercial buildings. A typical U.S. style suspended ceiling system with acoustic tiles is composed of grid members, boundary wall molding, hanger splay wires, and if braced, splay wire braces and compression posts. The grid system of a suspended ceiling consists of main inverted tee beams and inverted cross tee beams, made of light gauge steel, that interlock at locations of intersection and sit on light gauged L-shaped wall molding at its perimeter that is screwed to partition walls. A ceiling system in a low seismic zone has a minimum 9.5mm grid-wall molding clearance on all boundaries. The perimeter conditions of a seismically braced ceiling system are slightly different, and it has a minimum grid-wall molding clearance of a 19.1mm in on two adjacent boundaries and the other two boundaries have a fixed connection to the wall. This fixity is achieved using rivet fasteners to connect the grid members to the wall moldings on the fixed edges.

Acoustic ceiling tiles are manufactured out of a compressed high density mineral fiber material and are available in many shapes and sizes. The simplest tile geometry is a 0.61m x 0.61m square with a thickness ranging from 12.7mm to 19.1mm. The acoustic tiles are placed within the tee beam grid system, simply resting on the flange of each tee beam. The tiles are in no manner locked into place. Hanger wires are placed at 1.22m intervals and around the ceiling perimeter at no more than 20.3cm from the wall. The compression post and splay wire bracing is installed at 3.66m intervals beginning 1.83m from the wall. Fig. 1b) displays a schematic detail of the tee beam and bracing elements. A compression post is used in a bracing assembly to react against the vertical component of the splay wire braces. The hanger wires and splay wires of braced systems are made of 12 gauge wire that is looped through holes in main tee beams and connected to the supporting floor deck above the ceiling. The deck that serves as the support from which the ceiling system hangs varies greatly in commercial buildings. One prevalent floor deck throughout the U.S. is a corrugated steel deck with a concrete slab poured over it. This type of deck was chosen for the model in this study. The process and elements used for the analytical modeling of each of these suspended ceiling components is detailed in Chapter 3.

(a) An Example for Acoustic Tile Ceiling Systems



(b) Tee Beam and Bracing Components

Figure 1 Acoustic Tile Suspended Ceiling System Components (USG Corporation, 2006)

3. ANALITICAL MODEL ELEMENTS

The analytical model of a suspended ceiling system was created using SAP2000 (Computers and Structures, Inc, 2011), a structural analysis program with a wide variety of analysis and design options for creating simple and complex structural models. The model created for the analysis of suspended ceiling systems uses the built-in frame element and several types of linear and nonlinear link elements. The modeling assumptions of the ceiling systems discussed in the previous section are detailed throughout this chapter.

Tee Beam Grid System: The grid of T-beams is modeled using a series of beam elements with two separate cross sections for the main tees and cross tees. The cross section dimensions are consistent with the intermediate tee beam system produced by USG (USG Corporation, 2006) and are shown in Fig. 2a. All main tees within the ceiling system are 3.66m in length and placed at 1.22m on center. Two different lengths of cross tees are used; 1.22m cross tees are placed perpendicularly to the main tees at 0.61m on center, and 0.61m cross tees are placed parallel to the main tees at 1.22m on center. The main tee beam is continuous, but the 1.22m and 0.61m cross tees are pinned at each end. The plan view of the 13.4m^2 braced model is depicted in Fig. 2b) where the bold lines represent the main tees, the solid black lines represent the 1.22m cross tees, and the dashed lines represent the 0.61m cross tees.

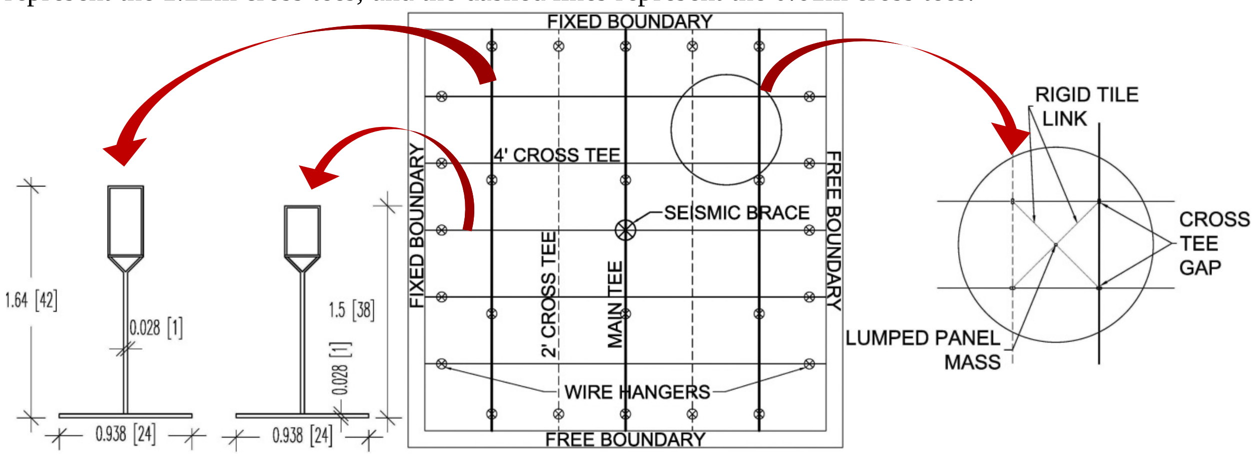


Figure 2. (a)Tee Beam Cross Sections, (b) 13.4m^2 Braced Ceiling Layout, and (c) 0.61m x 0.61m Ceiling Panel

Ceiling Tiles: The 0.61m x 0.61m acoustic ceiling tiles are modeled with an x-shape assembly with a lumped translational-rotational mass placed at the center joint that is rigidly connected to four corner joints. Fig. 2c displays the lumped mass at the center joint and rigid link configuration used for each tile. The weight of the ceiling tiles is assumed to be 5.1kg/m^2 to be consistent with experimental testing conducted at the University of Buffalo (Reinhorn et. al., 2012). The tiles are assumed to be 19.1mm thick, giving each tile a weight of 1.9kg. Translational and rotational mass for each tile were calculated and applied at the location of the tile center.

Hanger Wires and Brace Components: The 12 gauge wire hangers are modeled using the Hook Link (Computers and Structures, Inc, 2011) to resist only tensile forces. They are assigned a tensile stiffness but all the other degrees of freedom left free. The axial stiffness takes into account the loops created at each end of the wire where it is attached to the supporting floor deck and ceiling grid system. The axial stiffness of a single 1.22m long 12 gauge wire hanger is defined as, k_{hanger} = 33.7N/mm.

The modeling of the splay wires follows a similar process to the modeling of the wire hangers. The wire used for the splay bracing is also 12 gauge wire, and the wires are placed at a 45˚ angle and constrained to the deck 1.22m above the ceiling system. The tensile stiffness of a single splay wire is defined as, k_{splay} =

26.7N/mm. The compression post is modeled as a channel frame element with dimensions taken as an alternative to the telescoping compression post that is manufactured for the USG ceiling system. The dimensions for the channel section compression post are 19.1mm x 12.7mm x 1.5mm (USG Corporation, 2006).

Gaps and Boundary Conditions: The installation of acoustical suspended ceiling systems produces inherent gaps between the tiles and tee beams and at the boundaries of the system. These gaps are necessary to put tee beams and acoustical tiles into place. The gap size between ceiling tiles and tee beams was determined by using the actual dimensions of 0.60m x 0.60m of the nominal 0.61m x 0.61m ceiling tiles produced by USG (USG Corporation, 2006). The panel is assumed to be placed directly in the center of the 0.61m square grid leaving an equal 3.2mm gap on all sides. The horizontal gap in each direction is modeled using a horizontal T/C Friction Isolator Link (Computers and Structures, 2011). To allow for tile uplift when they are subjected to large upward accelerations, a Friction Isolator Link is used to connect the tile corners to grid intersection points (Fig. 3). The horizontal link is assigned a gap of 3.2mm. The horizontal links are assigned a horizontal coefficient of friction of 0.5 to capture the realistic tile-tee beam interaction. When the tile experiences uplift, it mechanically engages with the wider portion of the tee beam flange (Fig. 2). To capture this effect, the vertical coefficient of friction of horizontal links is increased to 1.0. The vertical link has no gap but is assigned an axial stiffness and a coefficient of friction for the translational degrees of freedom. The axial deformation of this vertical link is used to record the uplift of each tile corner resulting in tile dislodgement.

Linear Links (Computers and Structures, Inc, 2011) were used to model the main tee and cross tee splices. All translational degrees of freedom and torsion are fixed in for the cross tee splices. However, lateral and vertical rotations are assigned a very small stiffness of 6.2N-m/rad to improve the speed of numerical convergence. All degrees of freedom are fixed for the main tee splices.

Both the braced and unbraced tee beam grid systems have at least two boundaries that are not rigidly connected to the wall. The braced system has two free boundaries with a gap of 19.1mm, and the unbraced system has free boundaries on all sides with a gap of 9.5mm. The free boundary links are modeled using T/C Friction Isolator Links (Computers and Structures, Inc, 2011) and assigned their corresponding gap widths of 19.1mm for braced and 9.5mm for unbraced when the link is in compression. Because the grid is riveted to the wall molding at its fixed perimeter edges, the boundary links are fixed in their vertical degree of freedom. However, the links are free to displace horizontally and are assigned a coefficient of friction of 0.5 when moving in the horizontal plane

Supporting Floor Deck: The out-of-plane vibration of the supporting floor system is included in the model by assigning a composite deck cross section to a frame element and hanging the entire system from it. The section designer was used to create a cross section representing a 5.08cm composite steel deck with 11.43cm of concrete fill supported by W21x44 steel beams with a 3.05m tributary width. The size of the slab and number of girders is dependent on the size of the ceiling system being modeled. Because the cross section designed only includes one W21x40 beam and a 3.05m wide concrete slab, the cross sectional properties were modified so that the moment of inertia about the 3-axis and the mass and weight of the deck are quadrupled. Fig. 3 displays the completed model and the deck cross section.

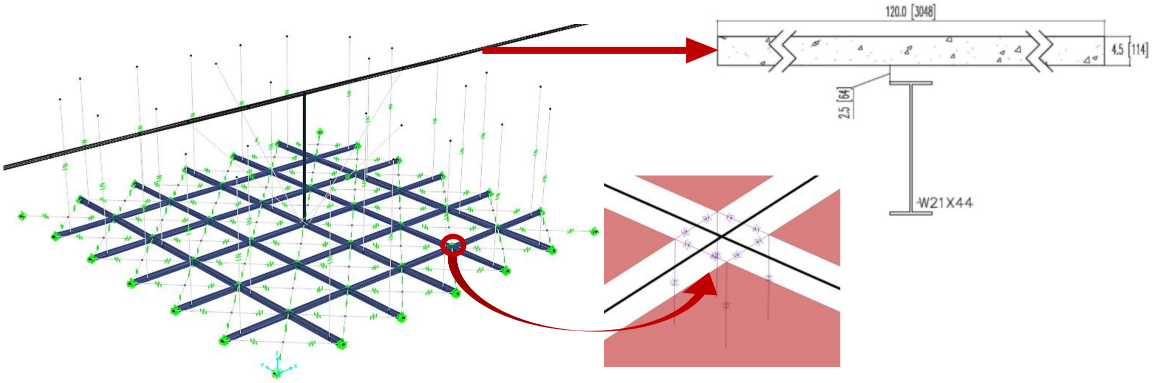


Figure 3. SAP2000 Model and Supporting Floor Deck

Due to some uncertainties associated with the components modeled within the system, sensitivity analyses were conducted for several of the elements. Sensitivity analyses were conducted to investigate the effects of the friction coefficient between ceiling tiles and tee beams, the ceiling panel weight, and the frequency of the supporting deck. The results of these sensitivity studies can be found in the following section.

4. SENSITIVITY ANALYSES

The maximum horizontal displacement at the center of the ceiling area and the maximum force experienced by the splay wire bracing are examined to determine the model's sensitivity to three parameters: friction between acoustic ceiling tiles and the tee beam grid, acoustic tile weight, and the frequency of the supporting deck. Time history cases with peak floor accelerations (PFA) of 0.7g, 1.7g, and 2.7g were chosen for the analyses.

Friction Coefficient: To investigate the sensitivity of the outputs to the assumed coefficient of friction between the ceiling tiles and tee beams, the model was reanalyzed using four friction values. The benchmark coefficient of friction, μ, for the ceiling system is assumed to be 0.5. To study the sensitivity of the ceiling model values of $\mu = 0$, $\mu = 0.75$, and $\mu = 1.0$ were assigned to the T/C Friction Isolator links used to simulate the gaps between tile corners and tee beam elements. The maximum force experienced by the bracing system and the maximum horizontal displacement at the center of the ceiling area showed similar sensitivity to the coefficient of friction between tiles and tee beams. Although the recorded brace force and displacement are greatest when the coefficient of friction is equal to zero, both parameters showed little sensitivity for all coefficient of friction values greater than zero. This type of behavior is expected as components are allowed to move freely when no friction is present. Evidence of the limited sensitivity is shown in Fig.4.

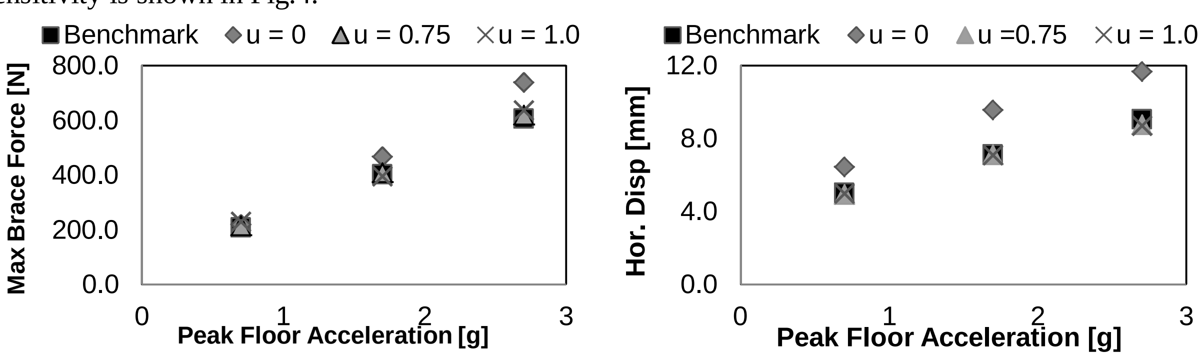


Figure 4. Sensitivity of Model to Friction Coefficient, (Left) Brace Force, (Right) Displacement at Center

Tile Weight: An increased weight and mass of 19.5kg/m^2 was assigned to the ceiling tiles to study the sensitivity of the model to the weight of the tiles. The heavy weight of 19.5kg/m^2 was chosen to remain consistent with the experimental tests conducted at the University of Buffalo (Reinhorn et. al., 2012). The additional weight resulted in a greater maximum force in the bracing system, and the maximum horizontal displacement at the center of the ceiling area is also greater for the system containing heavier tiles. This response is the consequence of the added inertial forces. The sensitivity results of the model can be seen in Fig. 5.

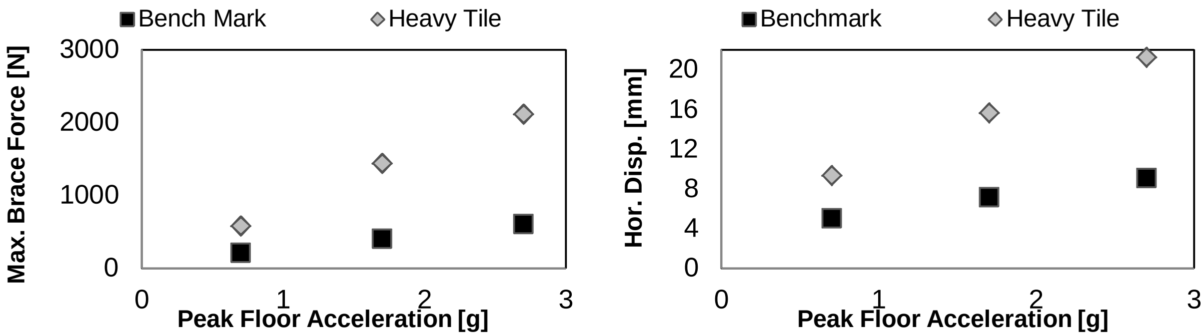


Figure 5. Sensitivity of Model to Ceiling Panel Weight, (Left) Brace Force, (Right) Displacement at Center

Deck Frequency: The range of natural frequencies for most constructed floor systems is 2.6 Hz to 18.4 Hz (Reinhorn et. al., 2010). The natural frequency of the supporting deck for the ceiling model is 8.8 Hz. The effect of a supporting deck with a low natural frequency was studied by decreasing the moment of inertia to reduce the frequency to 4.7Hz. The effect of a supporting deck with high frequency was studied by increasing the moment of inertia to increase the natural frequency to 12.9 Hz. This range of frequency analysis provides upper and lower bounds while remaining within the realistic frequency range of constructed floor systems.

The maximum force recorded in the bracing system showed some level of sensitivity to the frequency of supporting deck. The maximum brace force was greatest for the lowest frequency deck (4.7 Hz) and smallest for the highest frequency deck (12.9 Hz) although the high frequency deck and the benchmark model showed very similar brace forces. The frequency of the supporting deck showed little effect on maximum horizontal displacement of the ceiling system itself as shown in Fig. 6.

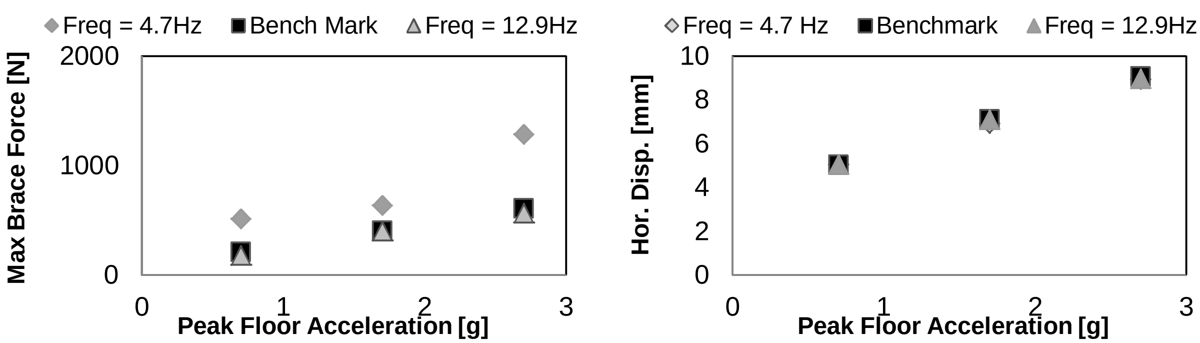


Figure 6. Sensitivity of Model to Deck Frequency, (Left) Brace Force, (Right) Displacement at Center

Only the sensitivity of the model to maximum brace force and maximum horizontal displacement of the ceiling system have been presented in this chapter. Sensitivity to vertical displacement of the ceiling system was also recorded, but no significant sensitivity was detected for any of the studied parameters. The time history load cases used for all sensitivity analyses correspond to load cases 3, 13, and 23 as described in the following section. The artificial acceleration time history generation for all load cases and application of these load cases for nonlinear time history analysis is outlined in Chapter 5.

5. MOTION GENERATION AND TIME HYSTORY ANALYSIS

Twenty-four artificial horizontal acceleration records and twenty-four artificial vertical acceleration records were generated by the computer program SIMQKE (VanMarcke et al, 1976). The target response spectrum was input in the form of a spectral velocity spectrum, and the output was obtained in the form of an acceleration record with a specified maximum acceleration value. The minimum period for the horizontal accelerations was defined as 0.03 seconds, and the maximum was defined as 3.0 seconds. The minimum period for the vertical accelerations was defined as 0.02 seconds, and the maximum was defined as 2.0 seconds. A trapezoidal intensity envelope with a rise time of 0.5 seconds, a level time of 3.5 seconds, and total duration of 5.0 seconds was specified for both horizontal and vertical motions (VanMarck et. al, 1976).

Acceleration spectra were produced for the horizontal directions following ICC-AC156 parameters. A height factor ratio of ½ was used for all acceleration records to simulate a floor acceleration occurring at mid height of a structure. Fig. 7a) displays the response spectrum generated from these parameters in the period domain

Where S_{DS} is the design spectral response acceleration at short period, as determined in Section 1613.5.4 of the IBC and z/h is the height factor ratio. A height factor ratio of ½ was used for all acceleration records to simulate a floor acceleration occurring at mid height of a structure. Fig. 7a) displays the response spectrum generated from these parameters in the period domain. The ICC-AC156 acceleration response spectrum was converted to a velocity response spectrum by dividing the acceleration points on the curve by their corresponding frequency.

The vertical acceleration response spectrum was produced following ASCE/SEI 7-05 New Chapter 23. The S_{DS} value used for the vertical response spectrum is obtained from the horizontal spectrum. ASCE Chapter 11 was used to correspond the vertical motion to the horizontal motion by determining S_{MS}, F_A, and S_S simultaneously. The vertical coefficient, C_V, is then determined from Table 23.1-1. Note: Site Class D, E, F was used for values of C_v. Fig. 7b) displays the vertical response spectrum from new Chapter 23 of ASCE/SEI 7-05.

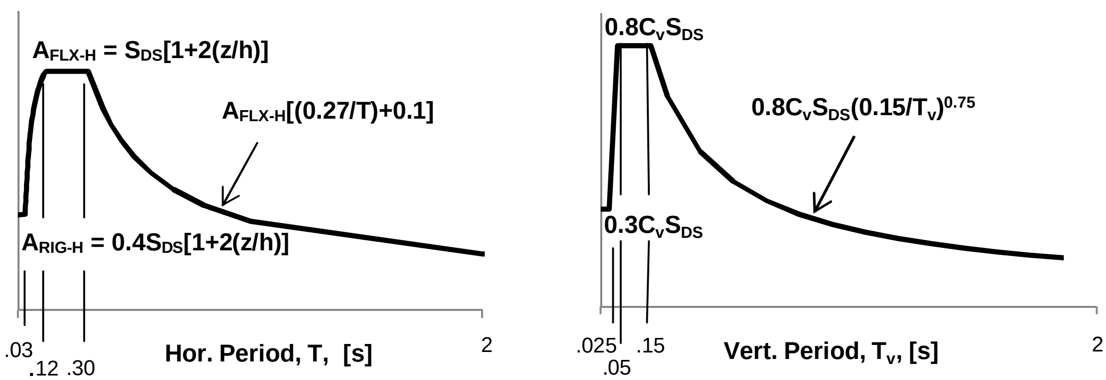


Figure 7. Design Response Spectra, (a) Horizontal Response Spectrum, (b) Vertical Response Spectrum

Upon the completion of the SIMQKE motion generation, the twenty-four horizontal and vertical acceleration histories were imported to Matlab where a 4th order Low Pass Butterworth filter and baseline correction were applied (MathWorks, 2010). The PFA of each motion was then recorded, and an experimental range of 0.5-2.8g for the horizontal acceleration records was selected for the nonlinear time history analysis. Twenty-four combinations of two horizontal acceleration records (one for the x-direction and one for the y-direction) and one vertical acceleration record were then imported as nonlinear time history analysis load cases in SAP2000. Each motion was multiplied by a scale factor to achieve its desired PFA with the units in/s^2. Table 1 displays the desired PFA, the SIMQKE generated PFA after filtering and baseline correction, and the scale factor applied to the motion to achieve the desired PFA with units in/s^2. Each load case is then set to run as SAP records the deformations, displacements, forces, and stresses experienced by each ceiling system element at each time step. The proportional mass and stiffness coefficients were set to provide 2% damping at frequencies of 6Hz and 15Hz. Carefully selected analysis results were then extracted and presented as fragility curves for the suspended ceiling system. These results are found in the following chapter.

Table 5.1. Sample Time History Load Cases with Scale Factors

	Horizontal Motion			**Vertical Motion**		
Case No.	**Desired PFA [g]**	**SIMQKE PFA [g]**	**Scale Factor**	**Desired PFA [g]**	**SIMQKE PFA [g]**	**Scale Factor**
1	0.5	1.046	184.74	.224	1.009	85.87
2	0.6	0.927	250.02	.294	1.021	111.37
3	0.7	1.030	265.67	.358	1.035	133.50
…	…	…		…	…	…
22	1.4	1.072	936.87	1.463	1.024	551.82
23	1.5	1.199	870.3163	1.519	0.960	611.52
24	1.6	1.002	1080.02	1.575	0.963	632.21

6. FRAGILITY STUDIES

Failure criteria are defined to produce fragility curves for each of the analytical models. Dislodgement limit state of the ceiling tiles can be determined from the horizontal and vertical displacements recorded at each corner of the ceiling tiles. Two displacement criteria must be met to record failure of a ceiling tile:

1. Either the horizontal gap between the tile and the tee beam in the x-direction must be closed, or the horizontal gap between the tile and the tee beam in the y-direction must be closed.
2. Vertical uplift of the tile must be greater than the total height of the cross tee section, 38.1mm

Review of the differences between regulations in low seismic regions with those of high seismic regions indicates a critical difference in the width of the perimeter wall-molding. The required width in low seismic categories is 22.2mm.The grid should be installed to leave a clear space of 9.5mm with a wall. This leaves a travel distance of 12.7mm before the grid of unbraced systems unseat. Therefore the unseating of tee beams, when moving away from the wall, followed by buckling of the tee beams in return, is a valid limit state. This was observed in the recent NEES-GC (Reinhorn et al, 2012) and NEES-TIPS tests in Japan (Soroushian, et al., 2012). The tee beams are assumed to unseat if the displacement of the end point exceeds 22.2mm-9.5mm=12.7mm.

The damage states used for the suspended ceiling are defined as:
DS1: 5% of tiles dislodge (Or 5% of perimeter tee beams unseat in the unbraced case)
DS2: 30% of tiles dislodge (Or 30% of perimeter tee beams unseat in the unbraced case)
DS3: Total ceiling and grid collapse. (Over 70% of tiles dislodge, or 70% of perimeter tee beams unseat in the unbraced case)

Fragility curves in Fig. 8a) and b) depict the probability of 5%, 30%, and total collapse of the 13.4m^2 ceiling system. The fragility curves for the unbraced system are shown in Fig 8a), and these curves take into account both fallen tiles and the unseating of tee beams at the perimeter. While the displacement of the tee beam grid at the free boundary of the braced system was recorded, there were no displacements great enough to cause unseating of the tee beam grid. Therefore, Fig 8b) displays the fragility curves of the seismically braced system which accounts for fallen tiles only. The unseating of the tee beam grid played a large role in the fragility of the unbraced system. As expected, a lower PFA is required to exceed a 50% probability of damage in the unbraced system than in the seismically braced system. While a 50% probability of total collapse arises for PFA values just greater than 1.5g for the unbraced system, it takes a PFA of near 3g to exceed a 50% probability of total collapse in the braced system.

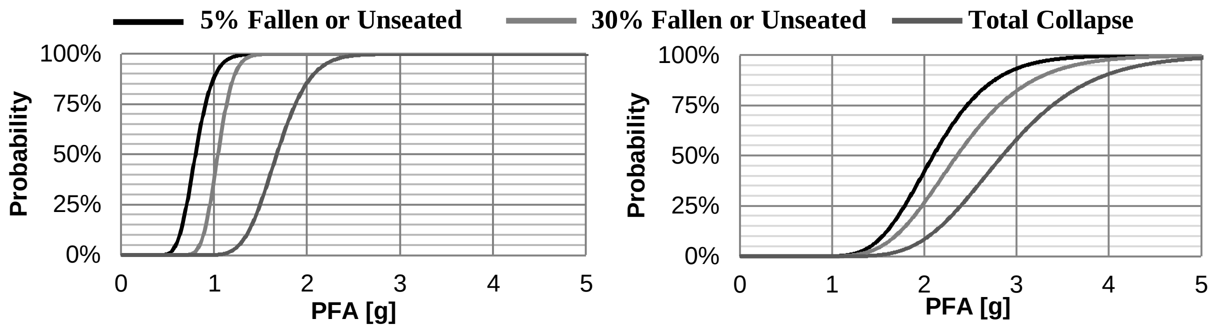


Figure 8. Fragility Curves of 13.4m^2 Ceiling Area, (a) Unbraced and (b)Braced

The effect of the seismic bracing on the uplift of the ceiling tiles was examined by comparing fragility curves that account for the vertical uplift of tile corners only. The comparison of these fragility curves is presented in Fig 9.It can be concluded that the addition of compression post and splay wires does not reduce the probability that ceiling tiles will experience uplift. In fact, a smaller PFA yields a 50% probability of all tiles exceeding the uplift limit in the braced system than in the unbraced system.

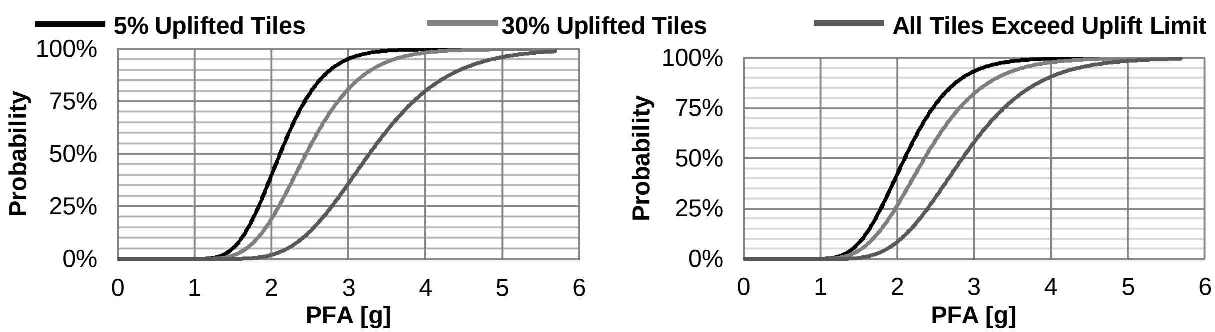


Figure 9. Fragility Curves of 13.4m^2 Ceiling Area Tile Uplift Only, (a) Unbraced and (b) Braced

The braced 72.8m^2 ceiling model was found to be least vulnerable to tile dislodgement during seismic excitation regardless of the seismic bracing condition. However, the unseating of the tee beam grid of the unbraced 72.8m^2 was found to be a critical limit state at very low values of PFA. The fragility curves of the 72.8m^2 unbraced ceiling area show high probabilities of damage at very low values of PFA. The fragility curves of the larger ceiling area are presented in Fig. 10.

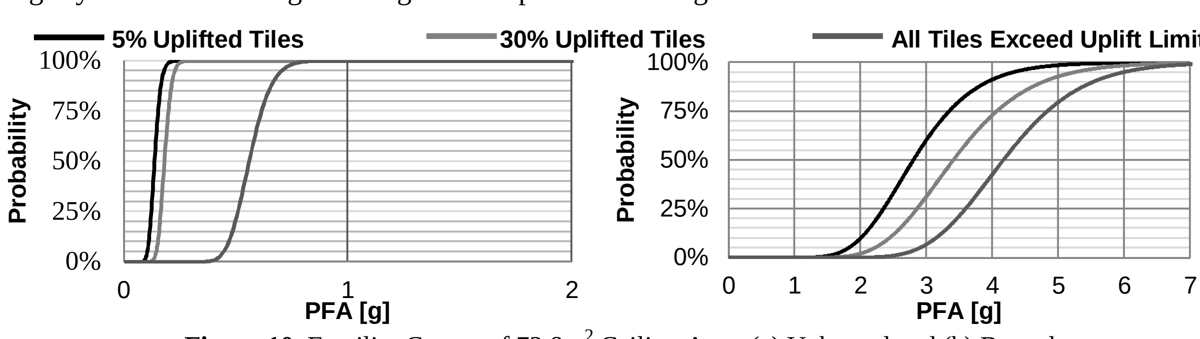


Figure 10. Fragility Curves of 72.8m^2 Ceiling Area, (a) Unbraced and (b) Braced

7. CONCLUSION AND FURTHER INVESTIGATION

The seismic fragility of 13.4m^2 and 72.8m^2 ceiling systems in the braced and unbraced condition were studied through an analytical model created using SAP2000 (Computers and Stuctures, Inc, 2011). Limit state criteria were set forth for the dislodgement of ceiling tiles and the unseating of the tee beam grid system of the unbraced ceiling areas. Damage states of 5%, 30%, and total collapse of the ceiling system were defined for the development of fragility curves for the larger and smaller ceiling areas. The curves show that the probability of damage in an unbraced system is higher than that of a braced system due to the unseating of the tee beam grid at the ceiling perimeter. However, when examining tile uplift only, the braced system induces tiles to exceed their uplift limit at a lower PFA than that of the unbraced system.

The fragility curves of the 72.8m^2 ceiling area show that a larger ceiling area is less vulnerable to tile dislodgement than a smaller ceiling area. However, comparison of results from the unbraced models show that the probability of damage due to the unseating of the tee beam grid is much greater at lower peak floor accelerations for the larger ceiling area.

The model presented does have limitations, and other possible failure limit states should be studied. The model does not have the ability to capture progressive collapse of ceiling systems, and it is recommended that advancements be made to study this phenomena. Experimental results have also indicated that forces at the fixed perimeter of braced systems may be greater than the capacities of the rivets used for connection to the wall molding. Failures at main tee and cross tee splices within the grid interior have also been sources of failure for experimental studies (Reinhorn et. al., 2012). Further studies should be conducted to include these additional modes of failure as limit states.

ACKNOWLEDGEMENT

Financial support for the work described in this report was provided by the National Science Foundation through the George E. Brown, Jr. Network for Earthquake Engineering Simulation Research (NEESR-GC) for Grand Challenge on Simulation of Seismic Performance of Nonstructural Components, Award #CMMI 0721399. This support is gratefully acknowledged. The authors also acknowledge the advice received from Bob Bachman and Lee Todesco who had valuable input for this study and Majid Kashani for his modeling assistance.

REFERENCES

American Society of Civil Engineers. (2005). ASCE/SEI 7-05, American Society of Civil Engineers

Computers and Structures, Inc. (2011). CSi Analysis Reference Manual, Computers and Structures, Inc

ICC Evaluation Service (2010). AC 156 Acceptance Criteria for Seismic Certification by Shake Table Testing of Nonstrucutral Components, ICC Evaluation Service

MathWorks. (2010). Matlab User Guide, The MathWorks, Inc

Reinhorn, Andrei M, Furnas, C., and Ryu, K.P. (2012). Seismic Behavior, Evaluation and Protection of Suspended Ceilings, University of Buffalo, NY.

Reinhorn, Andrei M., Ryu, K.P., and Maddaloni, G. (2010). Modeling and Seismic Evaluation of Nonstructural Components: Testing Frame for Evaluation of Suspended Ceiling Systems. *MCEER Technical Report.* **10-0004,** p. 1-183

Soroushian, S., et al., (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.

USG Corporation. (2006). Seismic Ceiling Resources Center. http://www.seismicceilings.com/seismic_online_tool.jsp?sec=features&navItem=0&yPos=32

VanMarcke, Dario, Gasparini, A., and Eric, H. (1976). SIMQKE User's Manual and Documentation, National Science Foundation.