Seismic Fragility of Suspended Ceiling Systems

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Full-scale dynamic testing of suspended ceiling systems was performed to obtain fragility data suitable for performance-based assessment and design. On the basis of the fragility data derived from testing, (1) the use of retainer clips improves the performance of ceiling systems in terms of loss of tiles, (2) including recycled cross tees in the suspension grid increases the vulnerability of the ceiling systems, (3) undersized (poorly fitting) tiles are substantially more vulnerable than properly fitted tiles, and (4) the use of compression posts improves the seismic performance of ceiling systems for the limit states of minor and moderate damage. Fragility curves are provided for four damage states. [DOI: 10.1193/1.2357626]

INTRODUCTION

Earthquake simulators are used for qualification and fragility testing of structural and nonstructural components. Seismic qualification is intended to demonstrate that a component is able to function during and after an earthquake. The objective of fragility testing is to establish a relationship between component performance and a representative seismic intensity measure.

The development of fragility curves often involves numerical analysis and/or physical observations. Numerical analysis of suspended ceiling systems is difficult because of both uncertainties in the physical behavior of elements and components once installed in the ceiling system and the highly nonlinear behavior of the elements and components once tiles are dislodged from the suspension grid. Physical observations of the seismic performance of in-service ceiling systems generally do not provide sufficient information to develop fragility curves because the levels of shaking imposed on the ceiling systems are not known. Consequently, full-scale experimentation is the only viable way to develop fragility curves for suspended ceiling systems.

GOAL AND OBJECTIVES

The main goal of the study reported in this paper was to develop seismic fragility curves for standard suspended ceiling systems to help enable performance-based seismic design and assessment of buildings.

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Fragility curves were developed by testing suspended ceiling systems on an earthquake simulator. The specific objectives of the study were to (1) characterize the seismic performance of suspended ceiling systems commonly installed in the United States; (2) evaluate improvements in seismic response due to the use of retainer clips that secure ceiling panels (tiles) to a suspension system; and (3) investigate the effectiveness of including vertical struts (or compression posts) as seismic reinforcement in ceiling systems.

The following sections present prior studies on suspended ceiling systems; information on the experimental facilities, test fixture, and test specimens; the procedure used to generate the earthquake histories for fragility testing; selected experimental results; and sample fragility curves. Much additional information can be found in Badillo et al. (2006).

Seismic codes, guidelines, and standards have been updated since the study described below was conducted in early 2003. However, the changes to the documents referenced below in the past three years have no significant impact on the results or conclusions of this study.

PRIOR STUDIES OF SUSPENDED CEILING SYSTEMS

ANCO Engineers Inc. (ANCO 1983) conducted an experiment in 1983 on the seismic performance of a 3.6 m × 8.5 m suspended ceiling system with intermediate-duty runners and lay-in tiles. The excitation used for the experiment was the 1953 Taft earthquake ground motion. The major finding was that the most common locations for damage in suspended ceiling systems were around the perimeter of a room at the intersection of the walls and ceilings, where the runners buckled or detached from the wall angle. The authors observed that the installation of vertical struts (compression posts) did not reduce the level of damage to the ceiling system.

Rihal and Granneman (1984) subjected a 3.66 m × 4.88 m suspended ceiling system to sinusoidal dynamic loading. The major findings of this study were that vertical struts reduced the vertical displacement response of the ceiling system and sway wires were effective in reducing the dynamic response of the suspended ceiling systems.

In 1993, Armstrong World Industries Inc. undertook a series of earthquake tests on a suspended ceiling system. These tests were performed by ANCO Engineers Inc. (ANCO 1993) on one 7.31 m × 4.26 m (24 ft × 14 ft) ceiling system using ground-motion histories that were representative of Seismic Zones 2A, 3, and 4 of the 1988 and later versions of the *Uniform Building Code* (ICBO 1991). A 30-second earthquake history was developed to represent the expected motions of the third and sixth floors of a six-story moment-resisting steel frame structure located on a soft soil site. Test amplitudes were then scaled up or down so that response spectra computed from measured input motions enveloped the in-structure floor response spectra for Zones 2A, 3, and 4 for nonstructural components supported within critical facilities. The main conclusion drawn from those studies was that the Armstrong ceiling systems tested on the earthquake simulator met the UBC Zone 4 design requirements for nonstructural components in essential facilities.

The seismic response of a set of 1.2 m × 4.0 m suspended ceiling systems was evaluated by Yao (2000). The main purpose of the study was to characterize the impact of installing sway wires in a suspended ceiling system. Testing revealed that the inclusion of 45° sway wires as recommended by the Ceiling and Interior System Contractors (CISCA 1992) did not produce a significant reduction in the seismic vulnerability of the ceiling system.

Armstrong World Industries Inc. has undertaken a series of earthquake qualification and fragility tests on suspended ceiling systems over the past five years. The tests were performed at the Structural Engineering and Earthquake Simulation Laboratory (SEESL) at the University at Buffalo (including Badillo et al. 2002, 2003a, b; Repp et al. 2003; and Gulec et al. 2005). A 4.88-m × 4.88-m (16-ft × 16-ft) square steel frame was constructed to test ceiling systems. Each of the ceiling systems was subjected to a set of combined horizontal and vertical earthquake excitations for the purpose of qualification. The procedures to qualify the ceiling systems in the period 2001 through late 2004 were those of the *ICBO-AC156 Acceptance Criteria for Seismic Qualification Testing of Nonstructural Components* (ICBO 2000). Two performance limit states were defined for the seismic qualification studies: loss of tiles and failure of the suspension system. The intensity of the earthquake shaking was characterized by the NEHRP short-period, maximum considered earthquake spectral acceleration, S_S (BSSC 2002, 2004). The target values of S_S ranged between 0.25 g and 1.75 g.

Although studies on ceiling systems have been performed over the past two decades, there are no widely available *fragility* data for suspended ceiling systems at this time, and no proven strategies to improve their seismic resilience. The studies described below attempt to partially fill these gaps in the knowledge.

EXPERIMENTAL FACILITIES AND TEST SPECIMENS

Fragility experiments were performed using a test fixture that simulated the horizontal and vertical stiffness of a typical story of a building. The test fixture was installed on an earthquake simulator and subjected to earthquake-acceleration histories as described below.

The earthquake simulator in the Structural Engineering and Earthquake Simulation Laboratory (SEESL) of University at Buffalo was used to evaluate and qualify the ceiling systems. The performance envelope of the simulator is ±152 mm (6 in.) displacement, ±762 mm/sec (30 in./sec) velocity, and 1.15 g acceleration at a payload of 197 kN (44 kips) in the horizontal direction, and ±76 mm (3 in.) displacement, ±508 mm/sec (20 in./sec) velocity, and 2.30 g acceleration in the vertical direction. For a payload of 489 kN (110 kips), the maximum platform accelerations are 0.55 g and 1.1 g in the horizontal and vertical directions, respectively.

A 4.88-m × 4.88-m (16-ft × 16-ft) square test fixture of ASTM Grade 50 steel was constructed to test the ceiling systems. A 3.8-cm × 3.8-cm (1-1/2-in. × 1-1/2-in.) angle was welded around the perimeter of the test fixture; a 5.1-cm × 15.2-cm (2-in. × 6-in.) timber ledger was attached to the angles to laterally restrain the ceiling system. The test fixture was designed to simulate one story and one bay of a building with ver-

Figure 1. Test fixture mounted on the simulator at the University at Buffalo.

tical floor frequencies in the range of 9 Hz to 12 Hz and horizontal frequencies in the range of 10 Hz to 16 Hz. Badillo (2003) and Badillo et al. (2006) provide a detailed description of the test fixture. Figure 1 is a photograph of the test fixture installed on the Buffalo simulator.

Each ceiling system consisted of two components: a suspension system and 49 tiles in seven rows of 7 tiles. Accelerometers and displacement transducers were used to monitor the response of the simulator platform, the test fixture, and the ceiling system.

The ceiling systems were installed in a grid that was hung with suspension wires from the top of the test frame. The grid was constructed with the Armstrong PRELUDE XL 23.8-mm (15/16-in.) exposed tee system. A 5.1-cm (2-in.) wall molding was attached to the perimeter timber ledger. The main runners and cross runners were attached to the wall molding with rivets on the south and west sides of the frame; the runners on the north and east sides were not restrained. The main runners were installed in the north-south direction at a spacing of 1.22 m (48 in.) on center. The 1.22-m (4-ft) cross runners were installed in the east-west direction at a spacing of 61 cm (24 in.) on center; the 6-cm (2-ft) cross runners were installed in the north-south direction at a spacing of 1.22 m (48 in.) on center. A compression post was placed 1.52 m (5 ft) from the south and east sides of the frame. The compression post was fastened to the main runner located in this position and extended up to the structural frame using 45° diagonal cables. Figure 2 presents details of the suspension system.

Depending on the level of quality control exercised in the manufacturing process, the size of a ceiling tile can differ significantly from its nominal dimensions. To study the impact of tile size on the seismic fragility of ceiling systems, two sizes of tiles were tested: *normal-sized* and *undersized* tiles. Ceiling tiles are considered by the manufacturers to be normal-sized if their plan dimensions are not smaller than the nominal dimensions by more than 6.4 mm (1/4 in.). If the tiles are smaller, they are considered to be undersized. One of the tiles tested was the Armstrong Fine Fissured HumiGuard Plus tile. This tile was smaller than the nominal size by at least 12.7 mm (1/2 in.) and was therefore considered to be an undersized tile for the purpose of this study. The other tile

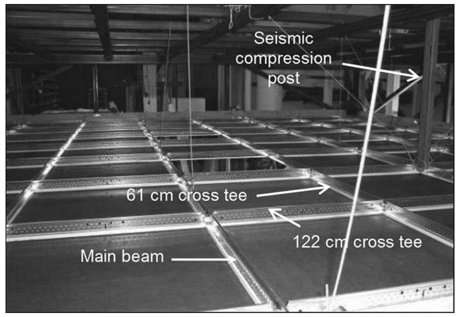


Figure 2. Suspension grid components.

used in this study was the Armstrong Dune HumiGuard Plus tile. This tile was a normal-sized tile. Table 1 presents summary information on each of the two tiles used in this study. Figure 3 shows the Dune HumiGuard Plus tile.

The retainer clips of Figure 4 were installed to investigate possible improvements in the seismic performance of suspended ceiling systems. These clips can be attached to main beams or cross tees behind lay-in ceiling tiles and help to prevent panel dislodgement. The key disadvantage of relying on retainer clips for improved seismic performance is that the clips are often removed for above-ceiling maintenance of mechanical, electrical, and piping systems, but then are not replaced (Phipps 2005). In this study, the clips were installed on the 1.22-m (4-ft) long cross tees of the grid.

The dynamic characteristics of the test frame were evaluated along the horizontal and vertical (programmable) of the earthquake-simulator platform using three methods: snap-back tests, resonance search, and white-noise tests. Badillo et al. (2006) provide information on the resonance-search and white-noise testing methods. Tables 2 and 3 list summary information for the horizontal and vertical first-mode frequencies and damping ratios, respectively, obtained using the three test methods. The modal frequencies fell within the range set by the authors for the design of the test fixture.

Table 1. Summary information on the tiles used in this study

Tile Name	Description	Panel dimensions [B, D, T] Nominal Size (cm)	Panel dimensions [B, D, T] Actual Size (cm)	Weight (kg/tile)
Fine Fissured	HumiGuard Plus mineral fiber tile	[61 × 61 × 1.6]	[59.7 × 59.7 × 1.6]	1.3
Dune	HumiGuard Plus mineral fiber tile	[61 × 61 × 1.6]	[60.3 × 60.3 × 1.6]	1.7

B, D, and T: breadth, depth, and thickness, respectively

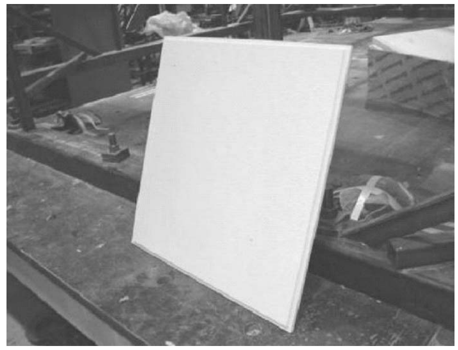


Figure 3. Tile Dune HumiGuard Plus.

SEISMIC QUALIFICATION AND FRAGILITY TESTING PROTOCOL

Numerous earthquake-simulator experiments were performed to develop fragility curves for standard suspended ceiling systems. Each experiment involved a set of horizontal and vertical (unidirectional and combined) earthquake excitations. The procedures to develop the earthquake histories generally followed the recommendations of the industry standard, *ICBO-AC156 Acceptance Criteria for Seismic Qualification Testing of Nonstructural Components* (ICBO 2000).[1] To qualify a test system, *ICBO-AC156* writes that a seismic qualification testing program must include a pre-test inspection and functional compliance verification, resonance search tests, random multifrequency seismic simulation tests, and post-test inspection and functional compliance verification. A similar protocol was adopted for the fragility testing described in this paper.

TARGET SPECTRA FOR QUALIFICATION AND FRAGILITY TESTING

Ceilings are typically suspended from floor slabs in buildings. Qualification and fragility testing should therefore employ acceleration histories that represent floor shaking and not ground shaking. *ICBO-AC156* was used as the basis for generating the floor acceleration histories that were input to the earthquake simulator.

A target or required response spectrum (RRS) must be defined for qualification testing. Earthquake histories are then matched to this spectrum. The ordinates of the *ICBO-AC156* RRS are defined by the short-period, maximum considered earthquake spectral acceleration, S_S, and the normalized ICBO (ICC) response spectrum shown in Figure 5.

For *design* earthquake shaking, the *International Building Code* (ICC 2000, 2003) defines the short-period spectral acceleration as

[1] AC-156 was revised and reissued by the International Code Council in 2004 (ICC 2004). The shape of the target spectrum (see Figure 5) was not changed in the period range of interest for ceiling systems and insignificant changes were made to the build, hold, and decay phases of the earthquake histories used for qualification (see Figure 6).

Figure 4. Retention clips.

$$S_{DS} = \frac{2}{3} F_a S_s \tag{1}$$

where F_a is the site coefficient, and S_S is the short-period, maximum considered earthquake spectral acceleration. Acceleration demands for testing components attached to floors are obtained per *ICBO-AC156* by assuming that the spectral acceleration of a rigid component, A_{RIG}, (assumed to have a frequency greater than 33 Hz) is given by Equation 2 and that of a flexible component, A_{FLX}, is given by Equation 3:

$$A_{RIG} = 0.4 S_{DS} \left(1 + 2 \frac{z}{h} \right) \leq 1.2 S_{DS} \tag{2}$$

$$A_{FLX} = S_{DS} \left(1 + 2 \frac{z}{h} \right) \leq 1.6 S_{DS} \tag{3}$$

where z is the height above the base of the building where the equipment or component is to be installed, and h is the height of the building. If the equipment or component is to be installed on the roof of a building, $z/h = 1.0$. If the location of the equipment or component in a building is unknown, or if it is being qualified for a general use in building structures, it is conservative, but appropriate, to set $z = h$. The ordinates of the vertical

Table 2. Fundamental frequencies obtained with the three test methods

	Test		
Direction	Snap Back	Resonance Search	White Noise
Horizontal	12.5 Hz	12.1 Hz	12.3 Hz
Vertical	9.6 Hz	9.6 Hz	9.5 Hz

Table 3. Damping ratios obtained with the three test methods

	Test		
Direction	Snap Back	Resonance Search	White Noise
Horizontal	2.6%	5.1%	4.7%
Vertical	0.5%	0.4%	0.7%

RRS are given by ICBO (2000) and ICC (2004) as two-thirds of those of the horizontal RRS, namely, A_{FLX}=1.07 g and A_{RIG}=0.80 g for S_S=1.00 g.

TESTING PROTOCOL FOR FRAGILITY TESTING

The testing protocol for fragility testing consisted of sets of horizontal and vertical excitations. Each set included unidirectional and bidirectional resonance search tests using white-noise excitation along the programmable orthogonal axes of the simulator platform (north-south and vertical). Each set of excitations also included a series of unidirectional and bidirectional earthquake motions that were established for different multiples of the RRS. The resonance search tests were undertaken to establish the natural frequencies of the ceiling systems. The ceiling systems were subjected to minor, moderate, and severe earthquake shaking for the purpose of identifying damage limit states as a function of earthquake intensity. The earthquake-shaking parameter selected to characterize the ground motion for input to the simulator was S_S per Equation 1, with target values ranging between 0.25 g and 2.5 g.

The earthquake excitations used for fragility testing were generated using the spectrum-matching procedure in STEX (MTS 1991). The spectral accelerations obtained with the matching procedure were scaled to envelope the target spectra over a frequency range from 1 to 33 Hz. Figure 6 presents the horizontal and vertical simulator-input ac-

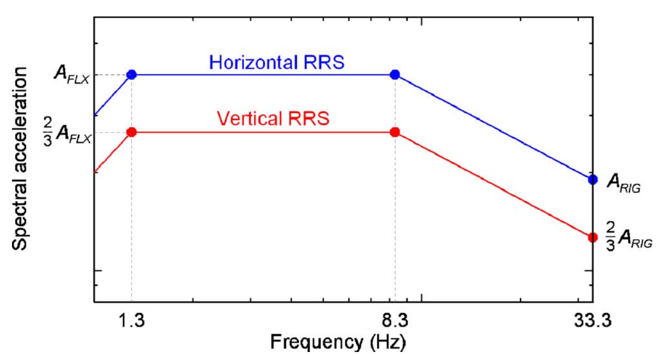


Figure 5. Required response spectra (RRS) for horizontal and vertical shaking (adapted from ICC, 2004).

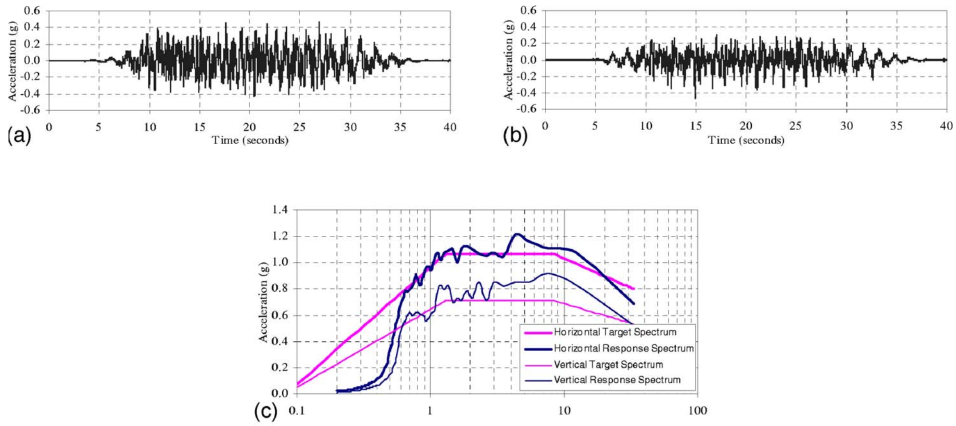


Figure 6. Earthquake histories and spectra for a level of shaking corresponding to S_S equal to 1.0 g. (a) horizontal acceleration; (b) vertical acceleration; (c) horizontal and vertical response spectra (target and calculated).

celeration records and their response spectra for a level of shaking corresponding to S_S equal to 1.0 g. Low frequency content was removed from the acceleration histories as needed to avoid exceeding the velocity and displacement limits of the earthquake simulator. Badillo et al. (2006) present additional information on the development of earthquake histories for fragility testing.

SIMULATOR TESTING OF SUSPENDED CEILING SYSTEMS

Four variables that affect the seismic performance of suspended ceiling systems were investigated herein: size and weight of tiles, use of retainer clips, installation of compression posts, and physical condition of grid components. Six ceiling system configurations were tested:

1. undersized tiles (4 systems)
2. undersized tiles with retainer clips (3 systems)
3. undersized tiles with recycled grid components (3 systems)
4. normal-sized tiles (6 systems)
5. normal-sized tiles with retainer clips (4 systems)
6. normal-sized tiles without the compression post (6 systems)

All tiles, connections, anchors, hanging wires, and splay wires were examined after each test. All damaged ceiling components (e.g., broken latches of cross tees, chipped tiles, etc.) were replaced prior to the following test. After each test cycle, the ceiling system (tiles and grid) was disassembled and then reassembled to return the ceiling system to a newly installed condition.

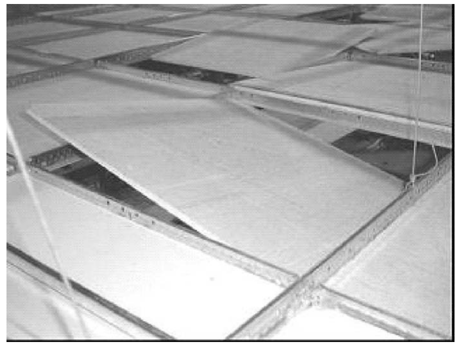


Figure 7. Tile rotating before falling, configuration 1.

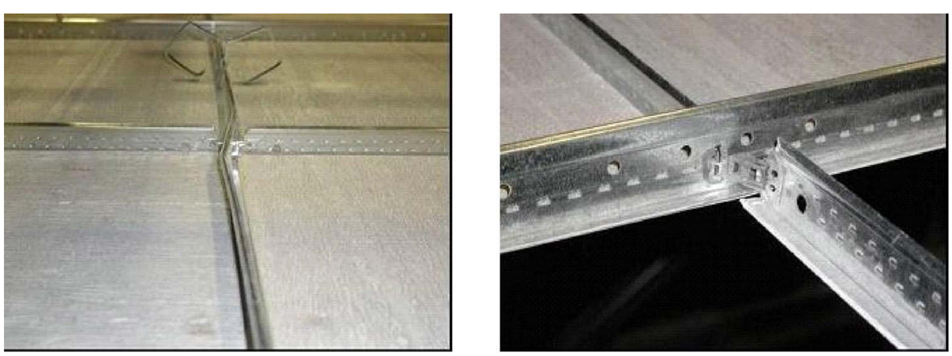
The addition of the ceiling tiles did not change the natural frequency of the test assembly in the horizontal direction (see Table 2) but did reduce the vertical frequency to approximately 6.7 Hz.

CONFIGURATION 1: UNDERSIZED TILES

The undersized tiles generally failed after popping up and out of the suspension grid. If the tiles did not fall back into their original position in the grid, the tiles typically rotated about their points of contact with the grid and fell to the simulator platform. Figure 7 shows a tile the instant in time before it fell from the suspension grid.

CONFIGURATION 2: UNDERSIZED TILES WITH RETAINER CLIPS

The retainer clips substantially improved the behavior of the suspended ceiling system in terms of loss of tiles by comparison with the systems of configuration 1. By re-



(a) Buckling in 4-ft cross tees (b) Damage to the latches

Figure 8. Damage to the cross tees when retainer clips were included in the ceiling system. (a) Buckling in 4-ft cross tees; (b) Damage to the latches.

taining the tiles, the clips increased the inertial loads on the grid, resulting in grid damage at lower levels of shaking. Figure 8a shows a buckled 1.22-m (4-ft) cross tee following a combined horizontal and vertical shaking test to S_S equal to 2.5 g. Another example of damage to the grid components is presented in Figure 8b, where the latches of the cross tees are shown bent and broken. In the three configuration 2 systems, tiles were lost primarily due to failure of grid components.

CONFIGURATION 3: UNDERSIZED TILES, RECYCLED GRID COMPONENTS

Including recycled cross tees in the assemblage of the suspended grid substantially increased the number of tiles that fell during the earthquake tests, by comparison with the systems in which only new grid components were used. Although the failure pattern of the tiles was similar to that of configuration 1, a greater number of tiles fell in configuration 3 because the latches that secured the connection between the cross tees did not lock completely, leaving the mechanical connection between the cross tees slightly loose.

CONFIGURATION 4: NORMAL-SIZED TILES

The number of tiles that fell during the earthquake tests of ceiling systems with undersized or poorly fitting tiles was substantially greater than in the systems equipped with normal-sized (snug) tiles. However, the components of the suspension grid suffered less damage in the systems with the undersized tiles because (1) the weight of the normal-sized tiles was larger (1.7 kg/tile vs. 1.3 kg/tile), and (2) more normal-sized tiles stayed in place for a given level of shaking, which increased the inertial load on the suspension grid. The buckling in the web of the 1.22-m (4-ft) cross tees was similar to the damage that the grid components experienced in configuration 2 (undersized tiles with clips) for higher levels of shaking. The tile failure pattern in configuration 4 was similar to that of configuration 1.

CONFIGURATION 5: NORMAL-SIZED TILES WITH RETAINER CLIPS

The damage produced by the unidirectional horizontal and vertical motions was minimal, concentrated in the components of the suspension grid. The retainer clips substantially improved the behavior of the ceiling systems in terms of loss of tiles by comparison with the systems of configuration 4, where clips were not included. The use of the retainer clips shifted the damage from the tiles to the suspension grid. The type of damage that was observed in the east-west 1.22-m (4-ft) cross tees of configuration 2 was also observed in the systems of configuration 5. In both systems, the loss of tiles was primarily due to the failure of components of the suspension grid. In one system (of four), a major failure in the suspension grid (see Figure 9), for combined shaking corresponding to S_S equal to 2.5 g, led to the loss of a considerable number of tiles.

Figure 9. Failure of grid and tiles in configuration 5.

CONFIGURATION 6: NORMAL-SIZED TILES WITHOUT COMPRESSION POST

The removal of the compression post made the suspension grid more flexible in the vertical direction. The utility of compression posts was judged by comparing responses from tests involving configurations 4 and 6. In some cases, the compression post reduced the degree of damage, but in other cases it did not.

Consider the results from tests in configurations 4 and 6. For combined horizontal and vertical shaking corresponding to S_S equal to 2.25 g in one system with a compression post (System N, per Badillo et al. [2006]), 4 tiles fell. For the same level of combined shaking in a system without a compression post (System X, per Badillo et al. [2006]), 11 tiles fell. This comparison suggests that the compression post is an effective means of reducing the number of falling tiles. However, for combined shaking corresponding to S_S equal to 2.50 g, 16 tiles fell in System N but only 10 fell for the same level of combined shaking in System X, a result that suggests that the installation of compression posts could lead to an increase in damage.

GENERAL OBSERVATIONS

- For the ceiling systems equipped with *undersized* tiles (configurations 1 through 3), the vertical excitation produced more damage than horizontal excitation, measured in terms of loss of tiles. The combined horizontal and vertical motions produced more damage than either of the unidirectional excitations.
- For the ceiling systems equipped with normal-sized tiles, the unidirectional (horizontal, vertical) motions produced minimal damage at high levels of shaking.
- The rivets that attached the main runners and cross tees to the wall molding of the test fixture played an important role in the seismic performance of the ceiling systems. When a rivet came loose or was destroyed during shaking, the damage in the ceiling systems in terms of loss of tiles was much larger than when all of the rivets were undamaged and the cross tees remained firmly attached to the wall molding.

- The main beams provide most of the stiffness in the suspension grid in the horizontal and vertical directions. However, the connections between the main beams were substantially more flexible than the beams. This is clearly reflected in the performance of the ceiling systems because the first few tiles to fall in most tests were those located around connections between two main beams.
- The removal of the compression post in the ceiling system equipped with normal-sized tiles increased the likelihood of exceeding the limit states of minor and moderate damage for a given level of earthquake shaking. For the limit states of major damage and grid failure, the removal of the compression post had little impact on the vulnerability of the ceiling system.

FRAGILITY ANALYSIS, LIMIT STATES, AND DATA EVALUATION

A fragility curve for a particular limit state is derived by computing the conditional probability of reaching or exceeding that limit state as a function of the excitation intensity (e.g., Singhal and Kiremidjian 1996, Reinhorn et al. 2001, Sasani and Der Kiureghian 2001). The conditional probability of reaching or exceeding a damage state is given by

$$P_{Lik} = P[D \geq d_{Li} | Y = y_k] \tag{4}$$

where P_{Lik} is the probability of damage reaching or exceeding damage limit state d_{Li} given that the excitation is y_k; D is a damage random variable defined on damage state vector $D=\{d_0, d_1, \ldots, d_n\}$; and Y is an excitation random variable.

LIMIT STATES

A limit state can describe, either qualitatively or quantitatively, the post-earthquake functionality (damage) of a component or system. Four limits states were defined herein to characterize the seismic response of ceiling systems. Limit states 1–3 account for the number (or percentage) of tiles that fell from the suspension grid. The fourth limit state is associated with structural damage to the suspension grid. These four limits states were termed (1) minor damage, (2) moderate damage, (3) major damage, and (4) grid failure. Specific definitions of these limits states are given below in terms of percentages of falling tiles and damage to grid components.

LIMIT STATE 1: MINOR DAMAGE

Limit state 1 is the loss of 1% of the tiles from the suspension grid: minor damage that should not impact the post-earthquake function of a building. This limit state might represent the permissible level of damage to ceiling systems installed in essential or special facilities (e.g., hospitals, computer and communication centers with fragile equipment, museums with valuable collection items, facilities with hazardous materials), where moderate levels of tile failure in the ceiling system could lead to evacuation of a building.

LIMIT STATE 2: MODERATE DAMAGE

Limit state 2 is the loss of 10% of the tiles from the suspension grid: damage that should not impact basic ingress/egress and life safety systems. Replacement of dislodged and fallen tiles would be required. Limit state 2 might represent a permissible level of damage in high occupancy, non-essential facilities.

LIMIT STATE 3: MAJOR DAMAGE

Limit state 3 is the loss of 33% of the tiles from the suspension grid. This limit state might be associated with the traditional building performance level of life safety. Large-scale replacement of tiles and grid components would be required. Limit state 3 might define the permissible damage to a ceiling system installed in low-occupancy, non-essential facilities.

LIMIT STATE 4: GRID FAILURE

Limit state 4 is a damage state associated with failure of part or the entire suspension grid. The definition of grid failure used here includes cross tees that fall, are bent, or have to be replaced because they compromise the structural integrity of the entire grid if left in place. Two types of grid failures have been observed in past testing: (1) isolated component failures, and (2) assembly failures involving multiple cross tees. In the case of isolated component failures, minor or moderate damage in terms of percent loss of tiles can occur because of grid failure. The repair effort can be significant when several isolated grid components are damaged, since disassembly of the ceiling system will be required for repair. However, the likelihood of life-threatening damage is low. For grid assembly failures, the damage can be extensive and the falling debris hazard might pose a life-safety hazard.

EVALUATION OF FRAGILITY DATA

The four limit states used to characterize the seismic performance of ceiling systems were selected with the intent of covering most of the performance levels described in current codes and guidelines with regulations for the seismic design of nonstructural components. Other limit states could be specified using the data of Badillo (2003) and Badillo et al. (2006).

Two intensity measures were used to construct fragility curves in this study: (1) peak horizontal acceleration, and (2) horizontal spectral accelerations at periods selected to embrace most in-service conditions for ceiling systems in buildings (=0.2, 0.5, 1.0, 1.5, and 2.0 seconds).

Fragility curves were developed for each of the six ceiling-system configurations tested in this study for the periods and limit states noted above. The procedure to develop the fragility curves for each configuration is illustrated in part in Figure 10. The data presented in the figure is from the six systems that formed configuration 4: systems L, M, N, O, R, and BB. The procedure is as follows:

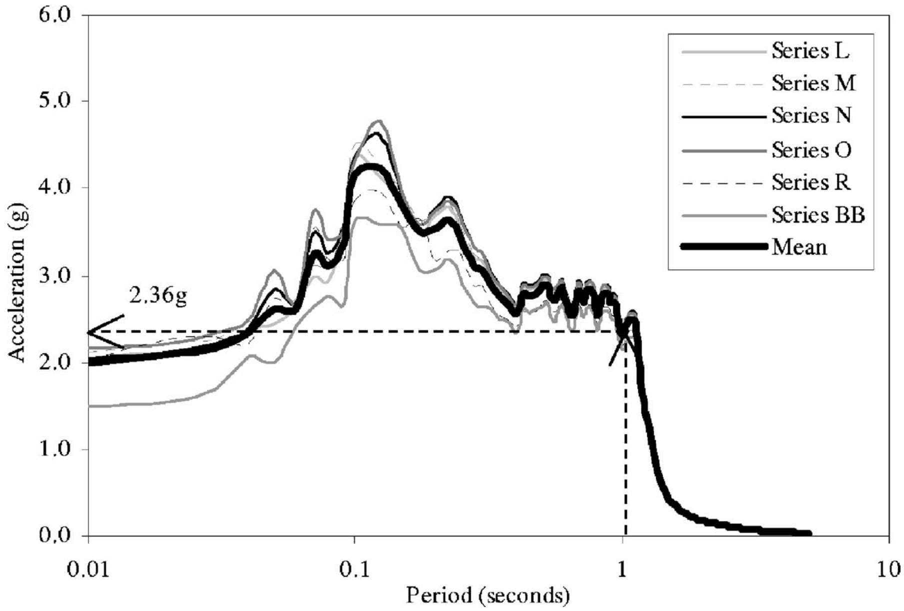
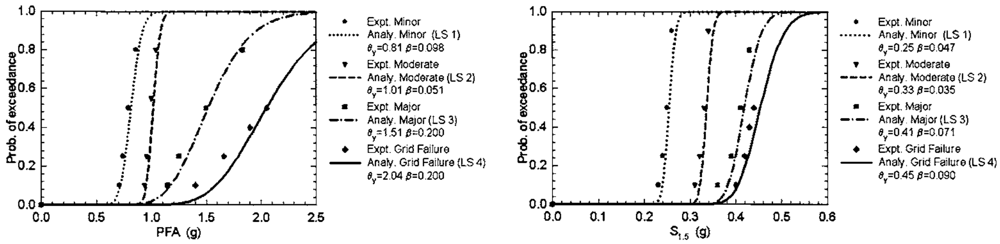


Figure 10. Part illustration of the procedure to develop fragility curves, configuration 4: normal-sized tiles.

- Obtain the mean spectral acceleration response for each shaking level using the response of the accelerometer mounted on the earthquake simulator.
- Compute the spectral accelerations at the selected periods (0.2, 0.5, 1.0, 1.5, and 2.0 seconds) from the mean spectral accelerations (see the arrows in Figure 10 for the one second calculation, $S_{1.0}$=2.36 g).
- Count the number of tiles that fell from the grid for each system (6 systems in this example) at each shaking level as a percentage of the total number of tiles in the ceiling system.
- Compare the percent tile failure with each limit state for each system.
- Calculate the probability (P_f) of reaching or exceeding the limit state as

$$P_f = \frac{N_f}{N} \tag{5}$$

where N_f is the number of systems (trials) where the limit state was reached or exceeded and N is the total number of systems (trials) in a ceiling system configuration. As N approaches infinity, P_f approaches the true probability of reaching or exceeding a limit state. The fragility curves were obtained by plotting the probability of reaching or exceeding a limit state for each shaking level versus the corresponding mean spectral acceleration.

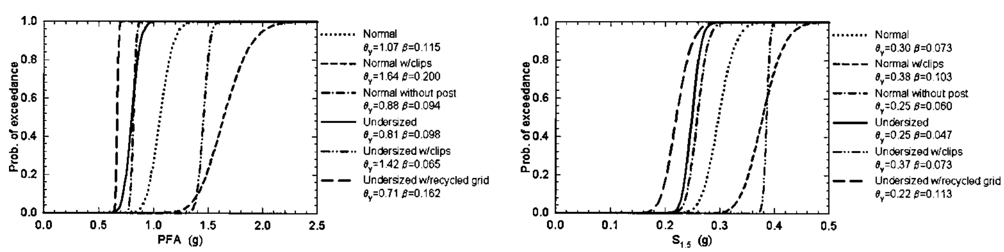


(a) Curves for peak floor acceleration (b) Curves for spectral acceleration at 1.5 seconds

Figure 11. Fragility curves for configuration 1: undersized tiles. (a) Curves for peak floor acceleration; (b) Curves for spectral acceleration at 1.5 seconds.

The fragility curves were developed as a function of spectral acceleration computed using acceleration histories recorded by an accelerometer mounted on the simulator platform. These curves overestimate the vulnerability of the ceiling systems because the systems were excited at multiple points (around the perimeter of the ledger beam and across the roof of the test fixture) by shaking more intense than that characterized by the accelerometer attached to the simulator platform. Badillo (2003) and Badillo et al. (2006) present information that can be used to judge the conservatisms introduced by the use of this accelerometer. Figure 11a presents the fragility curve for peak ground acceleration (0-second period spectral acceleration) and Figure 11b presents the fragility curve for the spectral period of 1.5 seconds, for configuration 1 and each of the four limit states. The smoothed curves of Figures 11a and 11b were generated using a lognormal distribution to match the test data of Badillo (2003) and Badillo et al. (2006), which are identified using solid symbols. The median value, θ, and logarithmic standard deviation, β, for each fragility curve are presented in these figures. Similar fragility curves and statistical data were generated for each of the periods listed above and for each of the six configurations; all are presented in Badillo et al. (2006).

Figure 12 presents similar information to that of Figure 11 but for each of the six configurations tested in this study, all for limit state 1 (minor damage). Accordingly, the



(a) Fragility curves for peak floor acceleration (b) Fragility curves for spectral acceleration at 1.5 seconds

Figure 12. Fragility curves for limit state 1: minor damage. (a) Fragility curves for peak floor acceleration; (b) Fragility curves for spectral acceleration at 1.5 seconds.

observed threshold values of damage differ from those values predicted by the use of the calibrated fragility curves.

FRAGILITY DATA INTERPRETATION AND DISCUSSION

This section examines the fragility data for each of the ceiling-system parameters considered in this study: (1) size of tiles, (2) use of retainer clips, (3) use of compression posts, and (4) physical condition of grid components. For the dependent limit states 1–3, the systems in a more severe state of damage constitute a subset of the systems in a state of lesser damage, and the fragilities at a specific ground motion intensity are always larger for the lesser state of damage than for the more severe condition, namely, the fragility curves do not cross. Limit state 4 is not dependent on limit states 1–3 because the fragility curve for limit state 4 crossed the curves for one or more of the ceiling tile limit states in selected cases (Badillo et al. 2006): grid components could fail without the loss of tiles. However, tile failure will depend to some degree on grid failure.

Fragility curves can also be employed indirectly to identify catastrophic failures. For example, accelerations beyond that associated with the intersection of curves for limit states 3 (major tile failure) and 4 (grid failure) should be avoided because the simultaneous failure of large sections of the suspension grid and a large number of tiles could cause serious injuries because the weight of the falling hazard is significant.

The fragility curves of Figure 12 can be used to compare the vulnerability of different ceiling-system assemblies for limit state 1: minor damage. For this limit state, the least vulnerable system was that of normal-sized tiles equipped with clips (configuration 5); the most vulnerable system was configuration 3, involving undersized tiles and recycled grid components. The retainer clips of Figure 4 substantially improved the resilience of the ceiling systems. The ceiling systems equipped with normal-sized tiles were more resilient than those equipped with undersized tiles. For this limit state, the addition of the compression post reduced the vulnerability of the ceiling system equipped with normal-sized tiles.

Table 4 lists the *threshold peak floor* accelerations associated with minor damage (1% tile loss), moderate damage (10% tile loss), major damage (33% tile loss) and grid failure for those ceiling-system configurations associated with new construction. The values of threshold peak floor acceleration reported in the table are those observed from testing and were not back-calculated from the calibrated fragility curves such as those shown in Figures 1 and 2. These data suggest that the ceiling systems tested as part of this study are not vulnerable to minor and moderate earthquake shaking.

SUMMARY AND CONCLUSIONS

Although the failure of suspended ceiling systems has been one of the most widely reported types of nonstructural damage in past earthquakes, there is little useful technical information available to the design professional on the seismic vulnerability of ceiling systems. Fragility-based methods were used herein to characterize the vulnerability of ceiling systems in a format suitable for performance-based seismic design. Full-scale

Table 4. Observed threshold peak floor accelerations[1] for damage in ceiling systems

Ceiling system	Configuration	Threshold peak floor acceleration (g) Minor damage	Moderate damage	Major damage	Grid failure
Undersized tiles	1	0.70	0.90	1.05	1.25
Undersized tiles with clips	2	1.25	NR[2]	NR[2]	1.10
Normal-sized tiles	4	0.85	1.05	1.60	1.25
Normal-sized tiles with clips	5	1.0	1.60	1.60	1.05
Normal-sized tiles w/out compression post	6	0.60	1.00	1.35	1.00

[1] Values rounded down to nearest 0.05 g
[2] Damage state not reached in testing program; >1.25 g

earthquake-simulator testing was performed to obtain fragility data for six ceiling systems. Four response limit states were defined using physical definitions of damage. The key conclusions of the study that is reported in detail by Badillo (2003) and Badillo et al. (2006) are listed below. These conclusions are based on laboratory testing using boundary conditions that will likely not be replicated exactly in the field. The reader is cautioned to extrapolate neither the results presented in this paper nor the conclusions listed below to either substantially different in-service conditions or different types of ceiling tiles and suspension grids.

- Ceiling systems constructed with either normal-sized or undersized tiles and equipped with compression posts are not vulnerable to minor and moderate earthquake shaking. (This conclusion is strictly applicable to the type and construction of ceiling systems tested as part of this study.)
- The use of retainer clips substantially improved the behavior of the suspended ceiling systems in terms of loss of tiles. However, by retaining the tiles, the use of clips increased the inertial loads on the grid, resulting in grid damage at lower levels of shaking. The loss of tiles in systems with retainer clips was due primarily to the failure of grid components. Alternate strategies for retaining ceiling tiles should be developed to alleviate concerns regarding the removal of clips during above ceiling maintenance of mechanical, electrical and plumbing systems.
- The use of recycled cross tees in the suspension system produced a significant increase in the number of tiles that fell during the earthquake tests because the locking-assembly latches that secured the connection between the cross tees did not lock completely, leaving the connection slightly loose. Components of a suspension system should not be re-used.
- The effect of a small variation in tile size on the performance of the ceiling systems was considerable. For a given level of shaking, the number of tiles that fell from the ceiling systems with undersized tiles was substantially larger than the number that fell from ceiling systems equipped with normal-sized tiles.

- The rivets that attached the main runners and cross tees to the wall molding played a very important role in the seismic performance of the ceiling systems. Damage to the ceiling systems in terms of loss of tiles increased significantly when the rivets connecting the cross tees to the wall molding failed.
- The installation of a compression post in the test fixture reduced the vulnerability of the ceiling system with normal-sized tiles for those limit states associated with minor and moderate loss of ceiling tiles. For limit states associated with more severe damage, the addition of the compression post did not substantially change the fragility of the ceiling system.
- Control of component-product and component-installation quality will play an important role in the vulnerability of in-service suspended ceiling systems.

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