

Seismic Fragility Testing of Suspended Ceiling Systems

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Summary

The failure of suspended ceiling systems (SCS) has been one of the most widely reported types of nonstructural damage in past earthquakes. In this research, fragility methods were used to characterize the vulnerability of SCS. Since SCS are not amenable to traditional structural analysis, full-scale experimental testing on an earthquake simulator was performed to obtain the fragility data. Four limit states of response were defined using physical definitions of damage. Based on the fragility data obtained, it was found that (a) the use of retainer clips improved the performance of SCS in terms of loss of tiles, (b) including recycled cross-tees in the assemblage of the suspended grid increased the vulnerability of the SCS, (c) undersized (poorly fitting) tiles are substantially more vulnerable than properly fitted tiles, and (d) including compression posts improves the seismic performance in SCS; however, the effectiveness remains questionable when it is compared with the required installation efforts.

Introduction

The response of nonstructural components can significantly affect the functionality of a building after an earthquake, even when the structural components are undamaged. Poor performance of nonstructural components in past earthquakes has led to the evacuation of buildings, to substantial economic losses due to business interruption and, in extreme cases, to the loss of life. Reconnaissance following past earthquakes has shown that failures of ceiling systems during earthquakes have caused significant economic losses and disruption in important or critical facilities.

The development of fragility curves generally involves the use of both mathematical modeling and physical observations. In the case of SCS, mathematical analysis is difficult to accomplish due to uncertainties in the physical behavior of elements and components of the system once they are installed in the ceiling system. Further, the complexity of the mathematical model and the highly nonlinear behavior of the components once tiles are dislodged make robust structural analysis of SCS unrealistic. Since analytical methods are generally not applicable to the study of SCS and data collected following past earthquakes are not suitable for fragility characterization, experimental methods represent the best and most reliable technique to obtain fragility curves for SCS.

Although several studies have indicated that some improvement in the seismic capacity of SCS has been achieved in recent years (Rihal and Granneman, 1984 and Yao 2000), there exists no robust fragility data and no proven strategies to increase the seismic strength of SCS. The main goal of this study was to develop fragility curves of SCS subjected to earthquake shaking. Fragility curves were

obtained by experimental testing of SCS on an earthquake simulator. The specific objectives of the research program were: (1) to study the performance of a SCS that is commonly installed in the United States, (2) to evaluate improvements in response offered by the use of retainer clips that secure the ceiling panels (tiles) to a suspension system, (3) to investigate the effectiveness of including a vertical strut (or compression post) as seismic reinforcement in ceiling systems, and (4) to evaluate the effect of different boundary conditions on the response of a SCS.

Experimental Facilities for Seismic Testing and Test Specimens

The earthquake simulator in the Structural Engineering and Earthquake Simulation Laboratory of the University at Buffalo was used to evaluate the SCS. A 16 x 16 ft square frame of ASTM Grade 50 steel was constructed to test the SCS. The frame was attached to the simulator platform. Figure 1 is a photograph of the test frame mounted on the earthquake simulator at the University at Buffalo.



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

Each ceiling system consisted of two key components: a suspension system and tiles. The ceiling systems were installed in a grid that was hung with suspension wires from the top of the test frame. A compression post was placed 5 ft from the south and east sides of the frame. Since the actual sizes of tiles may differ from the nominal size, two types of tiles were used for fragility testing in this study: normal sized if their plan dimensions are not smaller than the nominal dimensions by more than 1/4 in and undersized otherwise. One of the tiles tested was the Armstrong Fine Fissured tile (undersized). The other tile used in this study was the Armstrong Dune tile (normal sized). Table 1 presents summary information on each of the two tiles used in this study. Figure 2a is a photograph of the Dune tile. Clips similar to those shown in Figure 2b were installed to investigate possible improvements in the seismic performance of SCS.

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

| Tile name | Description | Panel dimensions [in.] | | Weight (lb/tile) |
|---------------|------------------------------|------------------------|-------------------------|------------------|
| | | Nominal size | Actual size | |
| Fine Fissured | HumiGuard Plus mineral fiber | [24 x 24 x 5/8] | [23-1/2 x 23-1/2 x 5/8] | 2.8 |
| Dune | HumiGuard Plus mineral fiber | [24 x 24 x 5/8] | [23-3/4 x 23-3/4 x 5/8] | 3.8 |

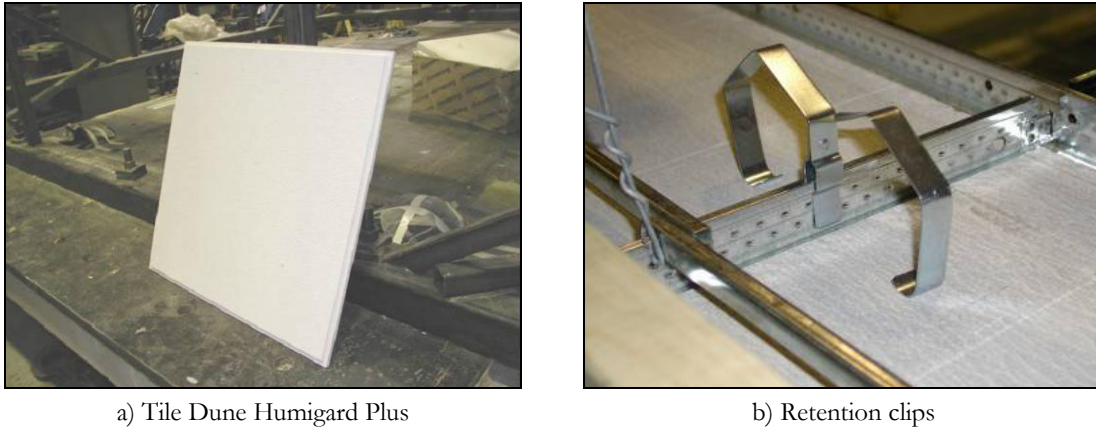


Figure 2. Tile and clips used in the fragility study

Seismic Qualification and Fragility Testing Protocol

The protocol for fragility testing followed the procedures set forth in the ICBO-AC156 “Acceptance Criteria for Seismic Qualification Testing of Nonstructural Components” (ICBO 2000). The first step to develop earthquake histories was to define a required response spectrum (RRS) as a function of the mapped spectral acceleration at short period S_s . For details, refer to ICBO (2000). The testing protocol for fragility testing consisted of sets of horizontal and vertical dynamic excitations. Each set included unidirectional and bi-directional resonance search tests using white noise excitation along the North-South and vertical directions. Each set of excitations also included a series of unidirectional and bi-directional spectrum-compatible earthquake motions that were established for different multiples of RRS. The parameter selected to characterize the ground motion for input to the simulator was the mapped spectral acceleration at short periods, S_s . The target of shaking levels ranged from a $S_s = 0.25$ g through $S_s = 2.5$ g. For details, refer to Badillo (2003). Figure 3 presents the horizontal and vertical response spectra (target and calculated) for a level of shaking corresponding to $S_s = 1.0$ g.

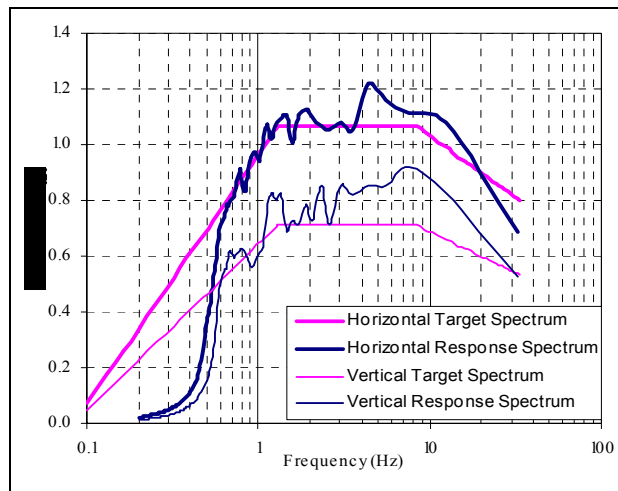


Figure 3. Response spectra (target and calculated) for a level of shaking corresponding to $S_s = 1.0$ g

Fragility Analysis and Data Evaluation

Four variables that affect the seismic performance of SCS were investigated in this study: (1) the size and weight of tiles, (2) the use of retainer clips, (3) the use of compression posts, and (4) the physical condition of grid components. A total of six set-ups were configured using different combinations of these variables: (1) undersized tiles (series A-D), (2) undersized tiles with retainer clips (series E-G), (3) undersized tiles with recycled grid components (series H-J), (4) normal sized tiles (series L-O, Q, R and BB), (5) normal sized tiles with retainer clips (series P and S-U) and (6) normal sized tiles without the compression post (series: V-Z and AA).

A fragility curve describes the probability of reaching or exceeding a damage (or limit) state at a specified level of excitation. Thus, a fragility curve for a particular limit state is obtained by computing the conditional probabilities of reaching or exceeding that limit state at various levels of excitation. A limit state is useful in describing the expected performance of a component or system when it is subjected to specific earthquake demands by characterizing the physical post-earthquake state of the component or structure. Limit states express qualitatively or quantitatively permissible levels of damage. Four limit states were defined in this study to characterize the seismic response of SCS. Limit states 1 through 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. The four limit states were: (1) minor damage (loss of 1% of the tiles from the grid), (2) moderate damage (loss of 10% of the tiles from the grid), (3) major damage (loss of 33% of the tiles from the grid), and (4) grid failure. Detailed descriptions of limit states are provided in Badillo (2003) and Badillo et al. (2003).

Several intensity parameters have been used in previous studies to create fragility curves, namely peak ground acceleration, peak ground velocity, spectral acceleration at specific periods, and spectral acceleration over a frequency range that would bracket the in-service dynamic properties of a specific system. In this study, two excitation parameters were used to construct the fragility curves presented below and in Badillo (2003) and Badillo et al. (2003): (1) peak ground acceleration, and (2) average horizontal spectral accelerations at selected periods. The selected periods represent a broad range that should include most in-service conditions for SCS in buildings: 0.2, 0.5, 1.0, 1.5 and 2.0 seconds. The spectral acceleration ordinates were obtained by calculating the mean spectral acceleration for each ceiling system configuration tested.

The procedure to develop the fragility curves for each configuration is as follows: (1) obtain the mean spectral acceleration response for each shaking level with the accelerometer mounted on the simulator platform, (2) compute the spectral accelerations at selected periods from the mean spectral accelerations, (3) count the number of tiles that fell from the grid for each system at each shaking level as a percentage of the total number of tiles in the ceiling system, (4) compare the percent tile failure with each limit state for each system, and (5) calculate the probability of reaching or exceeding the limit state.

Figures 4 and 5 present sample fragility curves developed using data from the earthquake simulator testing program. Figure 4a presents the fragility curve for peak ground acceleration, and Figure 4b presents the fragility curve for the spectral period of 1.5 seconds, for configuration 1 for each limit state defined earlier. Similar figures were obtained in this study for each of the spectral acceleration periods selected and for each of the six configurations. Figure 5 presents the same information as Figure 4, for each of the six configurations for the case 7 minor damage. Similar figures were

obtained in this study for each of the spectral acceleration periods selected and for each limit state defined. Some of the fragility curves were incomplete because the maximum acceleration, velocity, and displacement of the simulator are limited to 1.5 g, 94 cm/sec (37 in/sec) and 14 cm (5.5 in.), respectively. Different scales were used in plotting the fragility curves because the magnitude of the spectral acceleration changed substantially as a function of period.

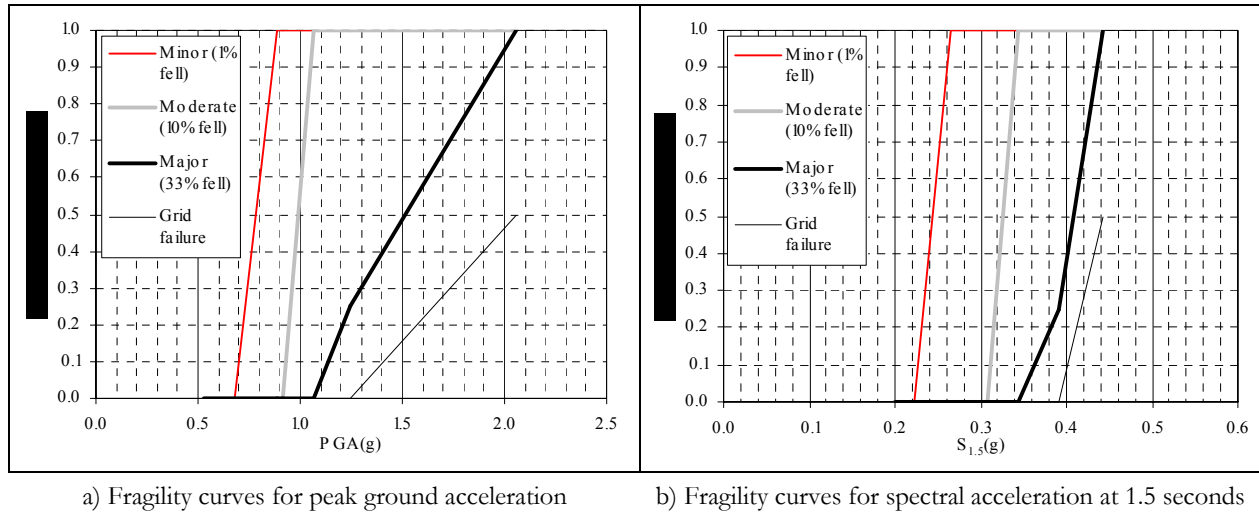


Figure 4. Fragility curves for configuration 1: undersized tiles

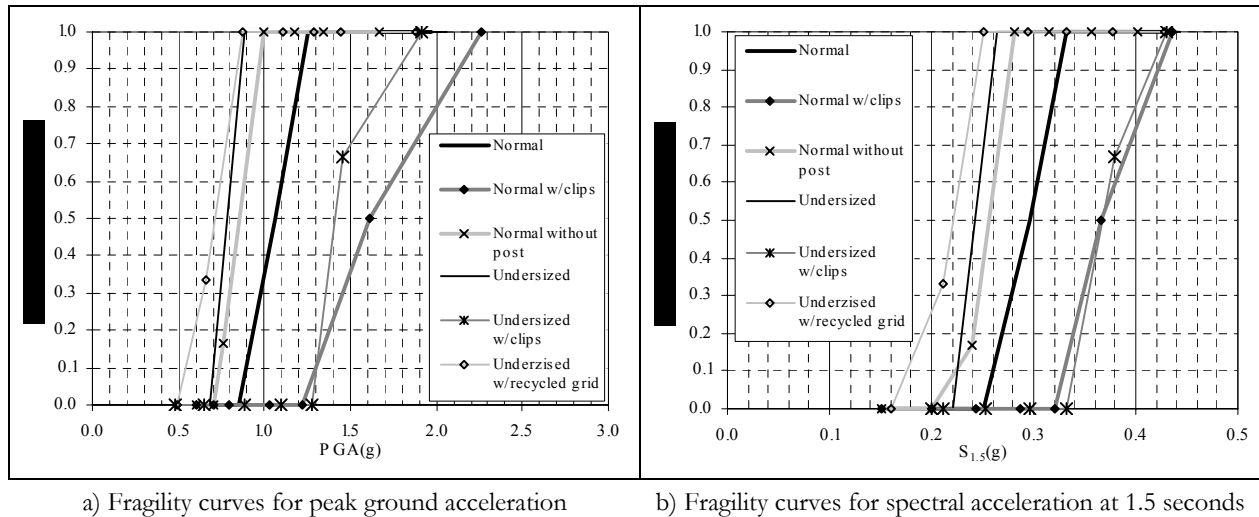


Figure 5. Fragility curves for limit state 1: minor damage

Concluding Remarks

The use of retainer clips substantially improved the behavior of the SCS in terms of loss of tiles. The loss of tiles in systems with retention clips was due primarily to the failure of 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. The number of tiles that fell during the shaking

tests of ceiling systems with undersized tiles was substantially larger in comparison to the systems equipped with normal sized tiles. Damage in the ceiling systems in terms of loss of tiles was much larger when a rivet failed than when all of the rivets were undamaged and the cross tees remained firmly attached to the wall molding. The region beyond the intersection of the fragility curves for limit state 3 (major tile failure) and limit state 4 (grid failure) should be avoided because failure of large sections of tiles and grid could cause a life-safety hazard. The usefulness of fragility curves was demonstrated when it was not clear from field observations whether including compression posts improved the seismic performance of the SCS. Using the fragility curves, it was clear that including the compression post in SCS improves the seismic performance of the systems in terms of reduced damage to the tiles and grid. However the effectiveness remains questionable when it is compared with the installation efforts that the compression post field assemblage requires. A more extensive testing program using different SCS configurations with and without seismic compression posts is recommended to give definitive conclusions.

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