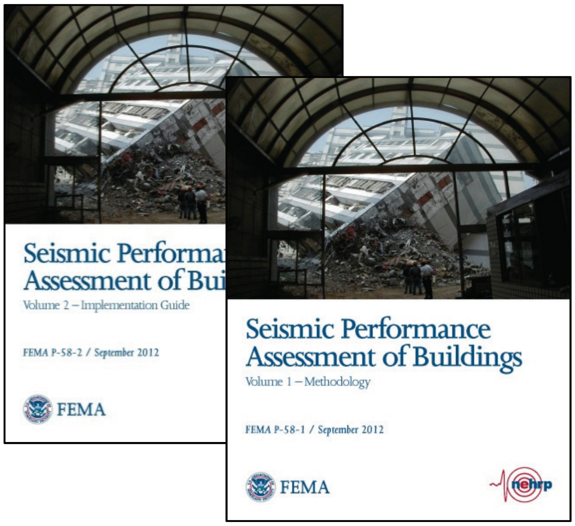

Background Document

FEMA P-58/BD-3.9.4

Development of Seismic Fragilities for Acoustical Tile or Lay-in Panel Suspended Ceilings

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Background Documentation

FEMA P-58 Background Documents are a series of reports documenting the technical background and source information for key aspects of the FEMA P-58 methodology and its implementation. These reports were developed over the course of the 10-year ATC-58/ATC-58-1 Projects funded under FEMA Contracts EMW-2001-RP-0056 and HSFEHQ-06-D-1105.

Background Documents were developed by consultants, serving at various levels within the project hierarchy, reporting the results of: (1) decisions on technical development protocols; (2) focused studies on the development of key aspects of the methodology; (3) documentation of recommended procedures; and (4) collection of available data for the development of structural and nonstructural fragilities. They were initially intended to serve as a record of the technical state-of-knowledge at the time they were produced, and as resources for the development of the eventual project reports. As such, they represent a snapshot in time, and may, or may not, match the technical content, recommended procedures, or data incorporated into the final methodology and its implementation.

This Background Document is intended for the purpose of providing supplemental knowledge to users of the FEMA P-58 methodology. Information contained herein has not been independently verified for accuracy as a stand-alone document, and may have been superseded in its final implementation within the methodology. Specifically in the case of certain nonstructural component fragilities, the NISTIR fragility classification numbering scheme was modified over the course of the project, and the fragility classification number assigned in this document might be different from numbers assigned in the final fragility database. Users of information in this document assume all liability arising from such use.

Notice

Cover illustration – Primary resource documents for the FEMA P-58 *Seismic Performance Assessment of Buildings, Methodology and Implementation* series of products: FEMA P-58-1, *Volume 1 – Methodology*, and FEMA P-58-2, *Volume 2 – Implementation Guide*.

Development of Seismic Fragilities for Acoustical Tile or Lay-in Panel Suspended Ceilings for the ATC-58 Project

Robert Bachman
ATC-58 Team Leader, Nonstructural Performance Products

Introduction

This document provides the basis for the seismic fragility values for acoustical tile or lay-in panel suspended ceilings (hereafter referred to as suspended ceilings) provided in the fragility spreadsheets for the ATC-58 project. Suspended ceilings are common in building construction and have been observed to be quite vulnerable during strong earthquake motions.

The history of suspended ceiling seismic research is summarized in Attachment 1 of this document which was prepared for the ATC-58 project by Keith Porter. It should be noted that while this previous research all provide valuable information, a current NSF research project called the Nonstructural NEES Grand Challenge project will provide the first definitive set of fragility values for a range of controlled demand motions, ceiling sizes and installation conditions. The project is currently doing full scale shake table testing of ceiling plan areas ranging in size from 16 feet x 16 feet to 50 feet by 20 feet for 1D, 2D and 3D directions of input motions. Sophisticated analytical simulations are also planned that will allow extrapolations to other conditions beyond those being tested. Only very preliminary data is currently available for the large 50 feet by 20 feet tests.

The large testing results provide some valuable insights. Ceiling failures appear to be primarily initiated at the riveted connections of the ceiling grid with perimeter angles. It was also observed that for a given grid installation condition, the heavier the tiles, the lower the ceiling grid seismic capacity. Therefore it appears from a simplistic viewpoint the ceiling system seismic capacity appears to approximately follow Newton's 2nd law of physics $F = ma$.

Because past research appeared to contained a lot of uncontrolled conditions such as inappropriate demand motions and did not provide a variety of ceiling areas, it was decided to develop the ATC-58 fragility values based on judgment in combination with the limited Nonstructural NEES Grand Challenge test data and observation provided to date. As the Grand Challenge completes its research in the next few years, it is expected much more justifiable values will become available and can be used in place of those being currently provided in the spreadsheets.

Fragility Demand Parameter

From all the research and testing that has been performed, it is apparent that suspended ceiling systems are sensitive to the accelerations motions to which the ceiling is attached. While it is likely that there is a narrow range of frequencies of input motion where ceilings are most sensitive, for purposes of ATC-58, the demand parameter selected in the development of spreadsheet fragilities is the peak horizontal floor acceleration of the floor above supporting the ceiling. The Grand Challenge project is utilizing the AC-156 Required Response Spectra (See Figure 1) as the shake table test motion at the ceiling support level. Special effort is made to adjust the table motion so that the AC-156 RRS is achieved at the ceiling support level. The testing used to establish the fragility values in the fragility spreadsheet are based on full 3 directional testing which is has been done in accordance with AC-156. The key acceleration parameter in AC-156 is the spectra acceleration denoted as A_{flx} in Figure 2. A_{flx} is the maximum 5% damped spectral acceleration for the frequency range between 0.8 and 8.3 Hz. It is reasonably assumed that the ceiling system maximum response is in this frequency range. In the Grand Challenge terminology, the maximum spectral acceleration is denoted as S.

From other unpublished studies, it appears that for a reasonable range of buildings the median averaged 5% damped floor spectra in the period range from 0.1 to 0.5 seconds is about 2.5 times the peak floor acceleration regardless of the whether the building is elastic or inelastic. Therefore for purpose of the ATC-58 Fragility Spreadsheet is assumed that the Peak Floor Acceleration (PFA) demand parameter is determined as:

$$\text{PFA (Major Ceiling Damage)} = S / 2.5$$

Damage States and Consequences

For purposes of the ATC-58 project, the following 3 damage states were adopted for the fragility spreadsheets.

Damage State 1 – 5% of ceiling tiles dislodge and fall – Consequence = reinstall tile

Damage State 2 - Ceiling grid and tile damage – Consequence = replacement for grid and tile for 30% of ceiling area

Damage State 3 - Major Ceiling Damage and some grid collapse – Consequence = total replacement of grid and tile

Currently, no fragility data is available from the Grand Challenge project of Damage States 1 and 2. The Badillo et. al.s research project at Buffalo (See Attachment 1) provided fragility values for 16 feet by 16 foot ceilings for 4 damage states similar to those above. However, the controls on demand motions were not the same as those in the Grand Challenge project so they have not been adopted for ATC-58. However, the values of the various damage states in the Badillo document compared to the damage states above provides the following insights. Damage State 1 (between Badillo's Limit State 1 and 2) occurs at demands in the range of 50% of the demands that cause Damage State 3 (Badillo's Limit State 3) and grid damage (Badillo's Limit State 4) occurs at demands in the range of 75% of the demands that cause Damage State 3. Therefore for purpose of the developing the ceiling fragility spreadsheets, it is assumed that

PFA (Damage State 1) = 0.5 PFA (Damage State 3)

PFA (Damage State 2) = 0.75 PFA (Damage State 3)

When the Grand Challenge results become available, it is expected that these assumptions will be replaced by actual justified data.

Ceiling Installation Types

For purposes of the ATC-58 project, two basic installation types were adopted for the fragility spreadsheets. These are no seismic bracing and detailing (typically found in Seismic Design Categories A, B and exempt area of other Seismic Design Categories) and seismically braced and detailed in accordance Seismic Design Category D, E and F requirements of ASCE 7-05 and ASTM E-580. Seismic Design Category C and requirements are between those of A, B and D, E. Since Grand Challenge Testing Data for C configurations, they have been assumed to be the same as A,B.

Specific Details of Seismically Unbraced Configuration (SDC A, B and C)

Perimeter Ledge Angle = 7/8 inch wide

Grid Duty = Intermediate

Diagonal Splay Wire Bracing = none

Compression Posts = none

Tile weight = less than 2 psf

Specific Details of Seismically Braced Configuration (SDC D, E and F)

Perimeter Ledge Angle = 7/8 inch wide

Grid Duty = Intermediate

Diagonal Splay Wire Bracing = yes

Compression Posts = yes

Tile weight = less than 2 psf

In addition it is assumed that that for Suspended Ceilings assigned SDC F, the ceiling system will be designed to higher design requirements and installed with rigorous Q/A and inspection.

Ceiling Installation Areas

Ceiling seismic codes and standards have provided increased seismic requirements based on ceiling area with greater detailing being required for larger ceiling areas. The ceiling areas with these ceiling requirements change are 144 square feet, 1000 square feet and 2500 square feet.

For purposes of the ATC-58 project, the following ceiling installation areas have been adopted for fragilities provided in the spreadsheets:

Ceiling Area

a. Less than 250 square feet

b. 250 – 1000 square feet

c. 1000 – 2500 square feet

d. Greater than 2500 square feet

Separate fragility values are developed for spreadsheets for each area. The 250 square foot area was adopted because of desires to not have normative quantities in any smaller units.

Fragility Value Determination Procedure

Based upon the preliminary observations and test data from the Grand Challenge project, it appears for current designs that the acceleration demand that causes the major damage state for suspended ceiling is inversely proportional to the tributary seismic force in the direction of motion at the intersection of the ceiling grid to the perimeter ledger angle. Therefore, the larger the tributary area and/or tile weight the smaller the acceleration demand to cause major ceiling damage. It is assumed that tributary area is directly proportional to the length, L of the ceiling in the direction of motion. At this point, the only controlled fragility data we have is for Damage State 3 from the Grand Challenge Project is a for a ceiling which is 50 foot long and 20 wide which is being tested in the long direction. For this ceiling, the value of L is assumed to equal 50 feet. Adjusting for ceiling areas for similar installations with the same tile weight is assumed as follows:

$$\text{PFA-DS3}(L) = \text{PFA-DS3}(20\text{x}50) \times 50 / L$$

For the ceiling areas assumed above the plan aspect ratio is not provided. For purposes of establishing fragilities for these areas, it is assumed that the ceilings are square in plan. For square areas, the tributary length L = square root of the Ceiling Area. Since the ceiling areas are for a range of values, it was necessary in establishing the fragility values to assume a specific area for each range. The following are the values assumed and the resulting tributary length:

	Ceiling Area	Area Assumed	L (feet)
a.	Less than 250 square feet	250	16
b.	250 – 1000 square feet	625	25
c.	1000 – 2500 square feet	1764	42
d.	Greater than 2500 square feet	2500	50

Given the foregoing and the value of S for Damage State 3 from the Grand Challenge project for the 20 x 50 foot ceilings, the median fragility values were determined. From the Grand Challenge Preliminary Data

S = 1.75 for the unbraced ceiling configuration (Revised Test No. 8)

S = 2.25 for the braced ceiling configuration (Revised Test No. 4)

Therefore:

PFA-DS3 (unbraced) = 1.75 / 2.5 = 0.7 g's

PFA-DS3 (braced) = 2.25 / 2.5 = 0.9 g's

Further it is assumed by judgment that for SDC F with high Q/A

PFA-DS3 (SDC F) = 1.1 g's

Now scale factors to apply to these values based on ceiling area and damage state factors determined from the above are:

Scale Factors Applied to PFA-DS3 (20 x 50)

Ceiling Area	DS1	DS2	DS3
a.	1.56	2.34	3.125
b.	1.0	1.5	2.0
c.	0.595	0.89	1.19
d.	0.50	0.75	1.0

Dispersion Factors

From the literature review, it appears that ceiling system are likely to have a wide range of quality in their installations and that the tested ceilings are probably at the high end of installations. Therefore it was judged for ceilings assigned Seismic Design Categories A, B, C, D an E installation, the dispersion factor be taken as 0.5 and for Seismic Design Category F, the dispersion factor be taken as 0.4.

Conclusions

The resulting fragility values and dispersions used in the fragility spreadsheets for the ATC-58 project based on the above procedure are provided in Table 1 of this document. It is recognized that the values provided are based up a great many unsubstantiated assumptions, extrapolations and judgments. It is expected that Nonstructural NEES Grand Challenge project will provide in a few years much improved and substantiated fragility values for ceiling systems.

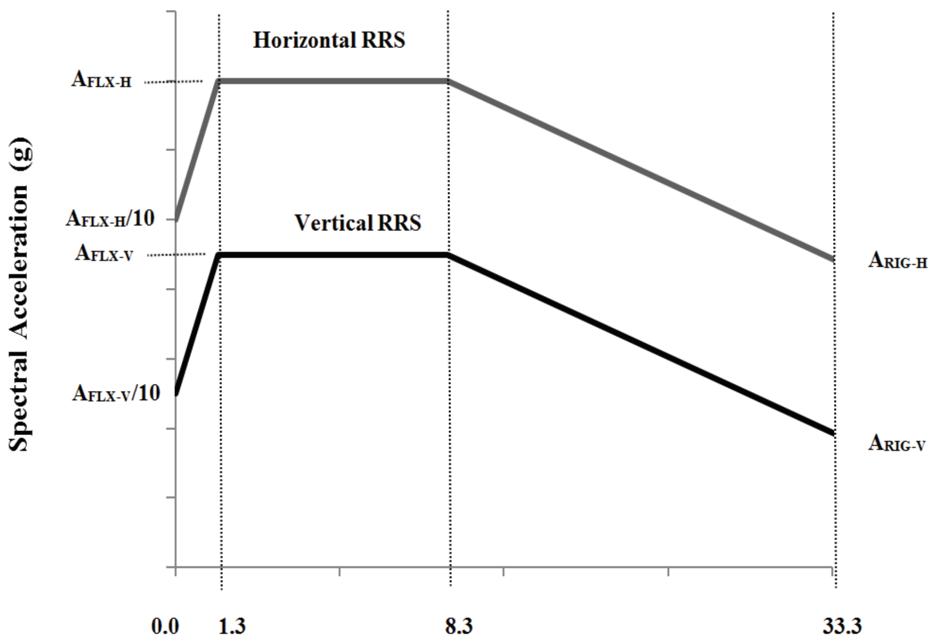

Figure 1. Required Test Response Spectra of AC-156 (5 % damped)

TABLE 1 – Recommend Suspended Ceiling Fragility Values

Fragility ID #	DS1		DS2		DS3	
	θ	β	θ	β	θ	β
C3032.001a	1.10	0.50	1.60	0.50	2.20	0.50
C3032.001b	0.70	0.50	1.05	0.50	1.40	0.50
C3032.001c	0.40	0.50	0.60	0.50	0.85	0.50
C3032.001d	0.35	0.50	0.50	0.50	0.70	0.50
C3032.002a	1.10	0.50	1.60	0.50	2.20	0.50
C3032.002b	0.70	0.50	1.05	0.50	1.40	0.50
C3032.002c	0.40	0.50	0.60	0.50	0.85	0.50
C3032.002d	0.35	0.50	0.50	0.50	0.70	0.50
C3032.003a	1.40	0.50	2.10	0.50	2.80	0.50
C3032.003b	0.90	0.50	1.35	0.50	1.80	0.50
C3032.003c	0.55	0.50	0.80	0.50	1.10	0.50
C3032.003d	0.45	0.50	0.65	0.50	0.90	0.50
C3032.004a	1.70	0.40	2.60	0.40	3.30	0.40
C3032.004b	1.10	0.40	1.65	0.40	2.20	0.40
C3032.004c	0.65	0.40	1.0	0.40	1.30	0.40
C3032.004d	0.55	0.40	0.80	0.40	1.10	0.40

ATTACHMENT 1- LITERATURE REVIEW OF CEILING RESEARCH

ANCO Engineers, Inc., (1983) performed full-scale shake-table tests on a light acoustical tile ceiling system. A variety of lateral restraint systems were tested, and the ceiling was subjected to a variety of shaking regimens. The report discusses ceiling performance under each test, providing peak diaphragm acceleration, peak ceiling acceleration, and horizontal peak response spectrum ordinate of actual table motion. Two tests produced incipient ceiling failure at 0.8g and 1.0g; the ceiling was tested to collapse in one test, at a peak diaphragm acceleration of 2.0g.

Rihal and Granneman (1984) present results of 12 full-scale dynamic tests of suspended ceilings under a variety of installation conditions. All tests are of a ceiling system 12 ft. x 16 ft. in plan, with 2 ft. x 4 ft. exposed grid elements and lay-in acoustical tiles. The authors find that the behavior of ceilings is influenced by input acceleration and frequency. They find that ceiling perimeter details significantly influence damage, and note that the presence of hangers near the ends of grid elements mitigates drop-out of ceiling tiles at the perimeter.

Griffin and Tong (1992) report observations of ceiling performance in more than 100 electric power and industrial facilities affected by the Loma Prieta and Whittier earthquakes. The authors present three major conclusions. First, ceiling damage was widespread, with more than half of these facilities experiencing some damage to suspended ceilings. Second, there is no obvious threshold of peak ground acceleration causing ceiling damage, with some damage occurring at PGA values below 0.10g, and some facilities experiencing no ceiling damage despite PGA in excess of 0.50g. Finally, all observed ceiling damage is attributable to tensile failure of grid connections, compression failure of grid elements, falling of above-ceiling components, and interaction of the ceiling with overhead utilities. The authors also note that perimeter connection of the grid to the wall acts as the de facto seismic restraint of the ceiling; diagonal bracing do not become active.

Eidinger and Goettel (1998) offer, without supporting evidence or a clear definition of damage states, fragility functions for suspended ceilings as a function of peak ground acceleration (not peak diaphragm acceleration). For the slight and complete damage states, which might correspond best to the DS1 and DS2 of interest here, they recommend PGA capacity values of 0.5g and 1.3g, respectively, with β = 0.5 and 0.4, respectively. Considering the commonly used zero-period acceleration amplification of 1.0 for the bottom 1/3rd of a building, 1.5 for the middle 1/3rd, and 2 for the top 1/3rd of a building, these median values might reasonably correspond to x_m = 0.8g and 2.0g in terms of peak diaphragm acceleration. Note however that they accompany their recommended capacity for DS2 with the note, "add compression struts," suggesting that these capacities are for a ceiling system without compression struts.

Badillo-Almaraz et al. (2006) recently performed full-scale laboratory tests of 16x16-ft suspended ceilings specimens with sway braces at the ceiling's single compression strut, and six different configurations: (1) undersized tiles (i.e., tiles slightly smaller than their nominal dimensions), (2) undersized tiles with retainer clips, (3) undersized tiles with recycled grid components, (4) normal sized tiles, (5) normal sized tiles with retainer clips and (6) normal sized tiles without the (single) compression post. The test simulated wall capture all around, i.e., the ceiling perimeter support was not free to move relative to the frame. All ceilings had 2x2-ft tiles (4 times the size of the ceiling considered here), no lay-in light fixtures (which occur in the ATC-58 ceiling), and tiles with mass of either 0.94 psf or 0.72 psf (significantly lighter than the tiles considered here). Each specimen was subjected to a sequence of 33 excitation histories, including unidirectional and bidirectional (longitudinal and vertical) white-noise excitations, as well as unidirectional and bidirectional earthquake excitations with varying degrees of short-period spectral accelerations from 0.25g to 2.5g in 0.25-g increments. They created fragility functions for four damage states: (DS1) 1% of tiles fall; (DS2) 10% of tiles fall; (DS3) 33% of tiles fall; and (DS4) Part or all of grid collapses (meaning cross-tees are bent or fall or otherwise must be replaced).

The authors created empirical fragility functions for these damage states in terms of the 5%-damped spectral acceleration of the floor *below* the ceiling, not above, at periods ranging from 0 sec to 2.0 sec in 0.5-sec increments, but based on the observed transfer function from base of the frame (the slab below the ceiling) to the top of the frame (akin to the slab above), shown in Figure 1, the amplification at periods of interest (around 0.7 Hz for a mass suspended the same length as the wire), the amplification is perhaps 1.1x. Configurations 4 or 6 might be most relevant here. Considering peak floor below acceleration (PFA) as the EDP, the fragility functions for configuration 4, DS1, DS2, DS3, and DS4 produced for this configuration had median capacities in terms of PFA equal to 1.1, 1.4, 2.0, and 1.7g, respectively, or approximately x_m = 1.2, 1.5, 2.2, and 1.9g respectively for peak diaphragm acceleration for the floor above (PDA). The estimated logarithmic standard deviations were β = 0.12, 0.20, 0.14, and 0.11, respectively, which are probably low because of uniformity in design, construction, and excitation. Failure appeared primarily to be initiated by buckling of grid members and pop-rivet shear failure. Capacities for configuration 6 are almost identical, suggesting that the presence of a single compression post (on one grid member each way) made little difference to collapse.

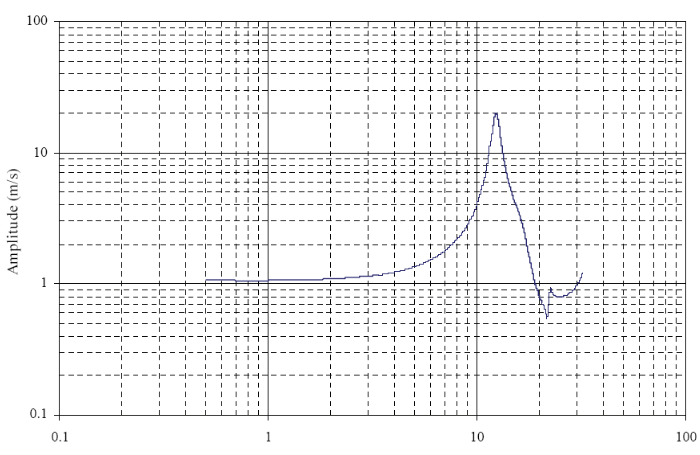

Figure 1. Amplification between table and top of frame (equivalent to the slab above) in Badillo-Almaraz et al. (2006) shake-table tests.

Porter (2000). As part of a doctoral thesis, the present author proposed an analytical methodology to estimate the fragility of suspended ceilings. It considered six possible failure modes (e.g., buckling of grid members, shearing of pop rivets, etc.), accounted for uncertainty in a number of variables, and made the median capacity a function of ceiling dimensions. Only a single ceiling system was considered, with 2x4 ceiling tiles (same unit weight as those considered here) and lay-in light fixtures of a particular weight and spacing. Monte Carlo simulation was used to generate samples of eight uncertain variables and to calculate six performance functions (one for each failure mode) and to determine collapse capacity as a function of ceiling dimensions (length and width) and peak diaphragm acceleration. It was found that the logarithmic standard deviation of collapse capacity was fairly constant ($\beta = 0.8$), and a curve was fit to the median capacity x_m, as a function of length + width. The model was compared with the empirical studies, which suggested that the model produced reasonable results.

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Suspended Components Study at University at Buffalo
August-October 2011

PRELIMINARY TEST RESULTS

1 Overview

A series of testing were planned in order to experimentally investigate the seismic behavior of a suspended ceiling system installed on a steel testing frame - new design and construction (20ft by 50ft., 10ft high) at UB-SEESL.

2 Objectives

The main objectives of the tests are as follows:

1. Identify failure modes describing functionality (limit states). The previously named limit states (Badillo, Whittaker and Reinhorn, 2003) are:
    a. dislocation of panels
    b. grid failure
    c. total collapse of a system
2. Measure engineering demands (i.e. forces) through accelerometers and load cells associated with the newly defined limit states.
3. Determine the effects/efficiency of various protective systems (i.e. bracing, compression struts, perimeter angles/clips, etc.) to improve limit states.
4. Investigate the influence of ceilings, lighting and other nonstructural installation conditions (i.e. plenum heights, panel weights, panel sizes, expansion joints)
5. Investigate the influence of input motions (i.e. uni-axial, biaxial and tri-axial, and AC156 RRS matched using random motions and/or sine sweep motions)
6. Investigate the influence of suspending roofs-floors' motions (i.e.in plane and out of plane for various boundary conditions)

3 Practice committee providing input to this project

Bill Holmes,
Robert Bachmann,
Dennis Alvarez (manufacturers and CISCA coordinator),
John Gillengerten,
Andre Filiatrault (liaison)
Manos Maragakis (PI - NEESGC)

4 Researchers

Andrei M. Reinhorn (project coordinator), K.P. Ryu (leading researcher, operator), Andre Filiatrault (PI)

5 Manufacturers(alphabetically):

Armstrong, Inc
Chicago Metallic, Inc
Marshall Corp
USG, Corporation

Table 1 - Test description (original)

	Ceiling Dimenstions										
Test Number	x, ft.	y, ft.	ht, z in.	Duty rating	*fixtures/ weight	bracing	comp. strut?	peri. angle condition	**Shaking Direction	**Design Condition	Comment
1	20	50	36	heavy	2x2 distributed	yes	yes	2" angle	y	SDC D	one D motion; mains in 20' direction Typ unless noted
2	20	50	36	heavy	2x2 distributed	yes	yes	2" angle	yz	SDC D	Add vertical
3	20	50	36	heavy	2x2 distributed	yes	yes	2" angle	xyz	SDC D	Investigate effedt of 3D motion
4	20	50	36	heavy	2x2 distributed	no	no	2" angle	xyz	SDC D	Investigate 1000 sf limit
5	20	50	36	heavy	2x2 distributed	no	no	7/8 angle/clips	xyz	SDC D	investigate effect of clips
6	20	50	36	heavy	2x4 linear	yes	yes	2" angle	xyz	SDC D	Investigate fixture pattern; Main in 50 ' direction 2 lines of fixtures in 20' direction
7	20	50	36	heavy	2x2 distributed	yes	no	2" angle	xyz	SDC D	investigate compression strut
8	20	50	72	heavy	2x2 distributed	yes	yes	7/8 angle/clips	xyz	SDC D	investigate deep plenum
9	20	50	36	intermediate	2x2 distributed	no	no	7/8 angle	xyz	SDC C	investigate typical SDC C conditions
10	20	50	36	intermediate	2x2 distributed	yes	yes	7/8 angel/clips	xyz	SDC D	investigate intermediate duty at SDC D

* fixtures, diffusers, and return air grills to be included to an average weight of 2.5 psf

** Shaking to be taken to max damage state. Intermediate damage states noted for purposes of establishing fragilities. Damage state also noted at appropriate SDC intensity

Shaking protocol to be determined.

Direction of shaking for tests 4-10 to be determined. XYZ assumed.

Table 2- Test description (updated list October, 2011) - [highlighted yellow:-completed]

		Ceiling Dimenstions											
Initial Planned Test Number	Actual / Revised Test Number	x, ft.	y, ft.	ht, z in.	Duty rating	TileWeight	*fixtures/ weight	bracing	comp. strut?	peri. angle condition	**Shaking Direction	**Design Condition	Comment
3	1	20	50	29	heavy	1.05	2x2 distributed	yes	yes	2" angle	**xyz**	SDC D	Investigate effedt of 3D motion
2	2	20	50	29	heavy	1.05	2x2 distributed	yes	yes	2" angle	**yz**	SDC D	Add vertical
1	3	20	50	29	heavy	1.05	2x2 distributed	yes	yes	2" angle	**y**	SDC D	One D motion; mains in 50' direction Typ unless noted
3 (Repeat)	4	20	50	29	heavy	1.05	2x2 distributed	yes	yes	2" angle	**xyz**	SDC D	Investigate effedt of 3D motion
4	5	20	50	29	heavy	1.05	2x2 distributed	**no**	**no**	2" angle	xyz	SDC D	Investigate 1000 sf limit
7	skipped	20	50	29	heavy	**3.00**	2x2 distributed	**no**	**no**	2" angle	xyz	SDC D	investigate compression strut
10	6	20	50	29	heavy	**4.00**	2x2 distributed	yes	yes	2" angle	xyz	SDC D	investigate heavy tiles at SDC D
5	7	20	50	29	heavy	1.05	2x2 distributed	**no**	**no**	**7/8 angle/clips**	xyz	SDC D	investigate effect of clips
9	8	20	50	29	**intermediate**	1.05	2x2 distributed	**no**	**no**	**7/8 angle**	xyz	SDC C	investigate typical SDC C conditions
6	9	20	50	29	heavy	1.05	**2x4 linear**	yes	yes	2" angle	xyz	SDC D	Investigate fixture pattern; Main in 50 ' direction 2 lines of fixtures in 20' direction
8	10	20	50	**65**	heavy	1.05	2x2 distributed	yes	yes	**7/8 angle/clips**	xyz	SDC D	investigate deep plenum

6 Testing Schedule - Completed

The experiments listed in Table 2 were completed by October 18, 2011

Activity / Testing	Duration	Tentative Schedule Start	End
Calibration & Set up: assembly of two frames, instrumentation (permanent channels), and metal adjustments **(COMPLETED)**	5 days	15-Aug	19-Aug
Bare Frame Testing - Instrumentation check and input motion preparation **(COMPLETED)**	3 days	22-Aug	26-Aug
#1 (#3 old designation): Test 3D + Instrumentation (removable and reinstall-able channels) + input motion check + redesign and correction of layout	10 days	29-Aug	9-Sep
#2 Test - 2D effects	5 days	12-Sep	20-Sep
#3 - (#1 old designation) Test 1D to failure	3 days	21-Sep	22-Sep
#4 - (Repeat test #1) with 3D	3 days	23-Sep	27-Sep
#5 - (Same as 1-4 without restrains - posts) with 3D -No Post	3 days	28-Sep	30-Sep
- (Same as 5 with heavy tiles 3 psf) with 3D **(SKIPPED)**	2-1/2 days		
#6 - (Same as 6 with heavier tiles 4 psf) with 3D	2-1/2 days	3- Oct	5-Oct
#7 - (Same as 4 with 7/8 angle and clips, no post)	2 days	6-Oct	7-Oct
#8- (NonSeismicdesign-IntermediateWeightGrid SDC C)	2 days	10-Oct	11-Oct
#9 (Same as #4 with 2x4 lights)	2 days	12-Oct	13-Oct
#10- (Same as 1-4 with larger plenum) with 3D	2 days	14-Oct	18-Oct

*Please see attached the test description Table 2 – Test description was prepared by the Practice Committee (modified by A.M.Reinhorn, 10/18/2011)

The test schedules followed a sequence of loadings as described in the TEST PROTOCOL which can be used as the Test Log.

Detailed description of the initial results and observations are presented in the next page

7 Preliminary Results of Testing

The tests were completed on October 18, 2011. The description of the tests is presented in Table 2 below.

A table showing the peak accelerations during testing at various locations is linked here

For each test a series of observations were prepared and marked on INSPECTION SKETCHES after each episode of progressively increasing intensity testing.

For each test a video of the failure was recorded (besides other intermediary videos)
The information is presented below along with the initial comments of the researchers:

TEST #1:

#1 (#3 old designation): Test 3D + Instrumentation (removable and removable channels check + input motion check + redesign and correction of layout **Video-T1-Sep 9-S=1.50**	29-Aug	9-Sep

Comments: This test was prepared for the calibration of the equipment, tuning the motions in the ceilings, testing the influence of variation of vertical input, learning how to do inspection and take notes, and fail the ceiling with increasing intensities with 3D motions, initially scheduled as Test #3. Due to early failure, probably caused by failure of rivets in the early preparation tests and previous vertical vibrations, this test will not be considered in the further evaluations of failure modes

TEST #2:

#2 - with 2D **Video-T2-Sep 20-S=2.75** **Inspection Sketches**	12-Sep	20-Sep

Comments: This test using the 2D-vertical and longitudinal motions as specified by AC156, showed early failure of the rivets on the east side (short side) gradually appearing at the end of the main runners, first in the unrestrained, then in the restrained ones. Total failure started near the side of the failed rivets.
It appears that the dynamic loads are collected by the main runners from a tributary area of 4 ft and transferred at the end of the runner or to the horizontal restrainers.

TEST #3:

#3 - (#1 old designation) with 1D **Video-T3-Sep 22-S=2.75** **Inspection Sketches**	21-Sep	22-Sep

Comments: This test using the 1D-longitudinal motion as specified by AC156, showed early failure of the rivets on the east side (fixed, short side) gradually appearing at the end of the main runners, first in the unrestrained, then in the restrained ones (as similar failure of Test#2). Total failure started near the east side of the failed rivets.

TEST #4:

#4 - (Repeat test #1) with 3D **(Video-T4-Sep 27-S=2.25)** **Inspection Sketches**	23-Sep	27-Sep

Comments: This test using the 3D-longitudinal, lateral, and vertical motions as specified by AC156, showed the effects of multi-directional input motions. The system collapsed at the slightly lower level than ones of Test #1 and Test #2. The initial failure occurred at the rivets on the east side (fixed, short side) gradually appearing at the end of the main runners, first in the unrestrained, then in the restrained ones (as similar failure of Test#2 and #3). Under the combined movements in the longitudinal and lateral directions, total failure occurred near the north side (fixed, long side).

TEST #5:

#5 - (Same as 1-4 without restrains - posts) with 3D -No Post **(Video-T5-Sep 30-S=2.00)** **Inspection Sketches**	28-Sep	30-Sep

Comments: This test using the 3D-longitudinal, lateral, and vertical motions as specified by AC156, was conducted without lateral restrainers (i.e. compression posts and splay wires). The initial failure occurred at the rivets of all the longitudinal main runners (grid) on the east side (fixed, short side). Total failure started near the north side (fixed, long side).

TEST #6:

#6 - (Same as 6 with heavier tiles 4 psf) with 3D **(Video-T6-Oct 5-S=1.50)** **Inspection Sketches**	3- Oct	5-Oct

Comments: This test using the 3D-longitudinal, lateral, and vertical motions as specified by AC156, showed the effects of heavy tiles. The initial failure occurred at the rivets on the east side (fixed, short side) at the lower level than the ones of any other testing and some of main runner splices were twisted. Total failure started in the middle of the ceiling system with severe damage to some of the cross T-ees (bent tabs).

TEST #7:

#7 - (Same as 4 with 7/8 angle and clips, no post) with 3D **(Video-T7-Oct 7 S=2.25)** **Inspection Sketches**	6-Oct	7-Oct

Comments: This test using the 3D-longitudinal, lateral, and vertical motions as specified by AC156, was conducted with the installation of 7/8" wall angles and seismic clips. The initial failure occurred at the grid joints (end of cross tees) on the east side (fixed, short side). Cross tee ends on the South side (floating side) were unseated from wall angles. Total failure started near the north-east corner (fixed-fixed-sides).

TEST #8:

#8- (NonSeismicdesign-IntermediateWeightGrid SDC C) with 3D 10-Oct 11-Oct
(Video-T8-Oct 11 S=1.75)) **(Video-T8-Oct 11 S=2.00)**
Inspection Sketches

Comments: This test using the 3D-longitudinal, lateral, and vertical motions as specified by AC156, was conducted with the setup of the Non-Seismic design-Intermediate Weight Grid for SDC C. The early failure occurred at the end of main runners on the east and west sides (short sides) first, which were unseated from wall angles, then ones on the South and north sides.
Total failure started near the perimeters of the middle north and south sides.

TEST #9:

#9 (Same as #4 with 2×4 lights) with 3D 12-Oct 13-Oct
(Video-T9-Oct 13 S=2.75)) **Inspection Sketches**

Comments: This test using the 3D-longitudinal, lateral, and vertical motions as specified by AC156, was conducted with the installation of 2×4 light fixtures in the short direction (north-south). The initial failure occurred at the rivets on the east side (fixed, short side) gradually appearing at the end of the main runners, first in the unrestrained, then in the restrained ones (as similar failure of Test#2 and #3). At the level of S_s=2.25g RRS, the center main runner splice broke and local vertical vibration in the center area of the system was observed during testing. Total failure started in the middle area and at the west and east sides independently but at the almost same time.

TEST #10:

#10- (Same as 1-4 with larger plenum) with 3D 14-Oct 18-Oct
(Video-T10-Oct 18 S=2.50) **Inspection Sketches**

Comments: This test using the 3D-longitudinal, lateral, and vertical motions as specified by AC156, was conducted with the setup of deep plenum (≈ 65” from the bottom of joists). 7/8 wall angles and seismic clips were installed. The early failure occurred at the end of main runners on the west side (floating side), which were unseated from wall angles. Vertical sagging between compression posts on the main runners was observed.
Total failure started near the perimeters of the middle south side (floating, long side).

8 Testing components configurations

See **Frame Configuration**, **Construction details** & **Grid Layout** (modified in agreement with rep of practice committee D. Alvarez (9/02/2011)
Additional **Grid Layout for 2x4** Lights was prepared 10/10/11 with input from practice committee)
All the installations follow the **INSTALLATION GUIDE** (Draft) and the **ASTM-E580** which has details of the connections and materials

9 Instrumentation layout and list

See **Instrumentation Plans** & **Instrumentation List**
Summary of Instrumentation

List	Permanent	Temporary*	Sum
Accelerometer	44	61	105
String Potentiometer	15	-	15
Displacement Potentiometer	-	16	16
Load Cells	-	20	20
Video	0	5	5
Total: 161 channels	59	102	161

* Temporary instruments (on ceiling systems) shall be prepared for easy removal and reinstallation on subsequent series (see details).
** Permanent instruments will be installed on the shake tables and test frames.

10 Test protocol -sequences of occurrence

See **Test Protocol-Schedule**

- Frequency searching - white noise testing, and/or sine sweep at low level
- Compensated motions at top corners of the test frame for AC156 RRS matched using *Random motions* (traditional) and Sine sweep (new development) motions (RRS Levels Ss=1.00g)
- Addition test input motions may be used to investigate the response of the system; UB-NCS protocol and simulated floor motions (Retamales et al ,2008), and recorded floor motions (CSMIP, 2005) (see **test input motions**)
- Incremental AC156 RRS matched using *Random motions* and *Sine sweep* motions - alternating - (RRS Levels Ss=1.50g and increments by 50 or 25 %)
- Various vertical input motions (for one configuration and nondestructive testing)

Details of motion input histories are still in preparation before verification with the shaking system

11 Data structure design on local repository-using Reinhorn's Data Structure

All data is recorded in the (private) repository at University at Buffalo before transfer to the NEEShub repository, using an original **data structure** developed for projects directed by Andrei M Reinhorn

12 Other preparatory issues:

- Modification of frames to fit fails safe requirements and testing - completed successfully
- Align and coordinate manufacturer's supplies and assistance - completed

13 References:

Mosqueda G., Retamales R, Filiatrault A and Reinhorn, A.M. (2011), "Testing Protocol for Experimental Seismic Qualification of Distributed Nonstructural Systems", in *Earthquake Spectra*, 27(3), 835-856

Maddaloni G., Ryu K.P. and Reinhorn, A.M. (2011), "Shake Table Simulation of Floor Response Spectra" in *Int. Journal of Earthquake Engineering and Structural Dynamics,* 40(6), 591-604

Reinhorn, A.M. Ryu K.P. and Maddaloni G., (2010), "Modeling and Seismic Evaluation of Nonstructural Components: Testing Frame for Experimental Evaluation of Suspended Ceiling Systems", *MCEER Technical Report –MCEER-10-0004*, University at Buffalo – the State University of New York

Retamales, R., Mosqueda, G., Filiatrault, A., and Reinhorn, A.M. (2008), "New Experimental Capabilities and Loading Protocols for Seismic Qualification and Fragility Assessment of Nonstructural Components", Technical Report MCEER-08-0026, MCEER, University at Buffalo-the State University of New York, Buffalo, NY

CSMIP (2005). "Instrumented Building Response Analysis and 3-D Visualization System", John A. Martin & Associates, Inc., Los Angeles, CA.

Note 1: The installation of test frame, instrumentation, test planning and operations, data collection and management, processing and reporting is designed and scheduled by the NEESR project investigators. The supply and installation of ceilings is provided by the participating manufacturers, with assistance of lab personnel

Table 3 - Future tests on smaller frames (original plan) to be executed at latter time

Single Table Tests												
S1		12	12	36	heavy		2x2 distributed	none	yes	7/8 angle/clips	xyz	SDC D
S2		16	16	36	heavy		2x2 distributed	none	yes	7/8 angle/clips	xyz	SDC D
S3		20	20	36	heavy		2x2 distributed	none	yes	7/8 angle/clips	xyz	SDC D
S4		16	16	20	heavy		2x2 distributed	yes	yes	7/8 angle/clips	xyz	SDC D

ASTM E 580

SDC C Moderate EQ

SDC D Sever EQ

defined by ASCE7 and IBC. Seismic Design Category.

SDC C

1. Grid, T&C >= 60lb
2. Wall Angle >= 7/8in.
3. End wire <= 8in distance from perimeters
4. wire #12 spaced @ 4ft.
5. No fixed ends.(?)

SDC D

1. Grid, T&C >= 180lb
2. Wall Angle >= 2in.
3. End wire <= 8in distance from perimeters
4. wire #12 spaced @ 4ft.
5. Lateral force bracing > 1000 ft2
6. Seismic seperation joist > 2500 ft2